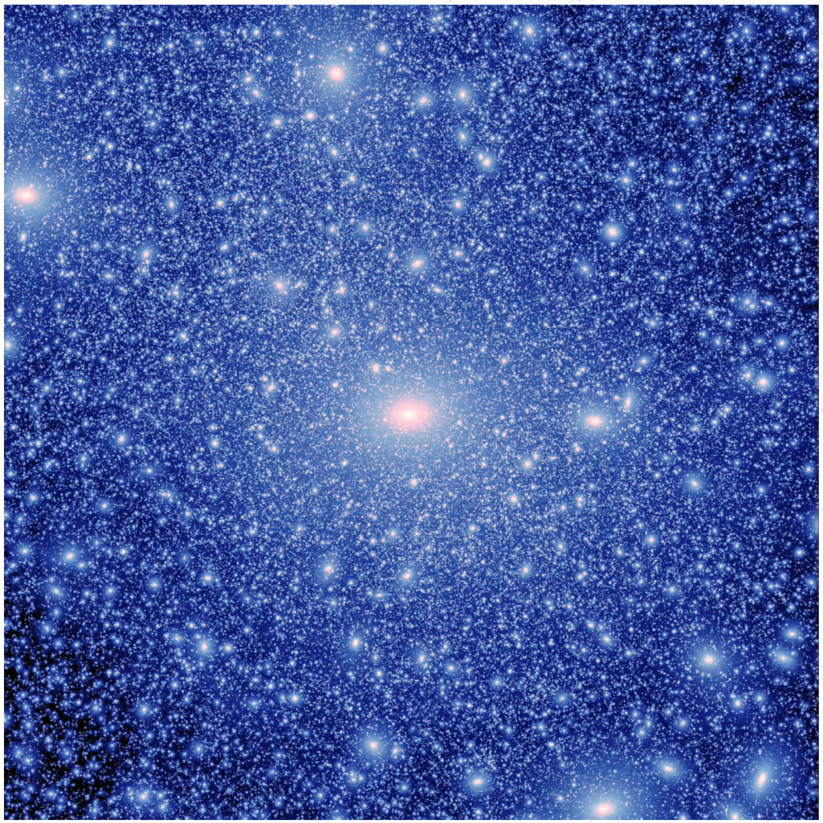
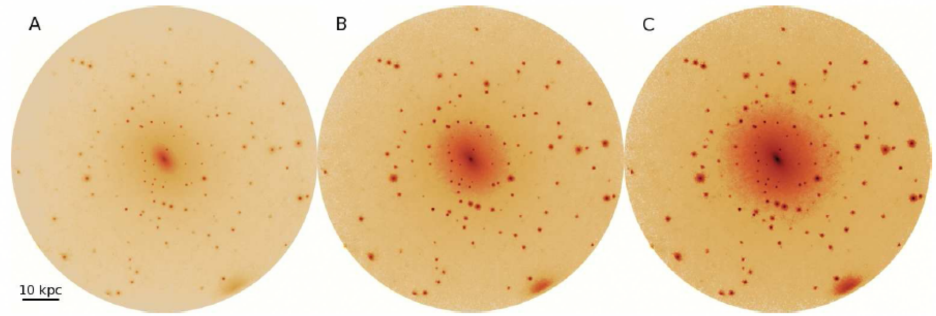
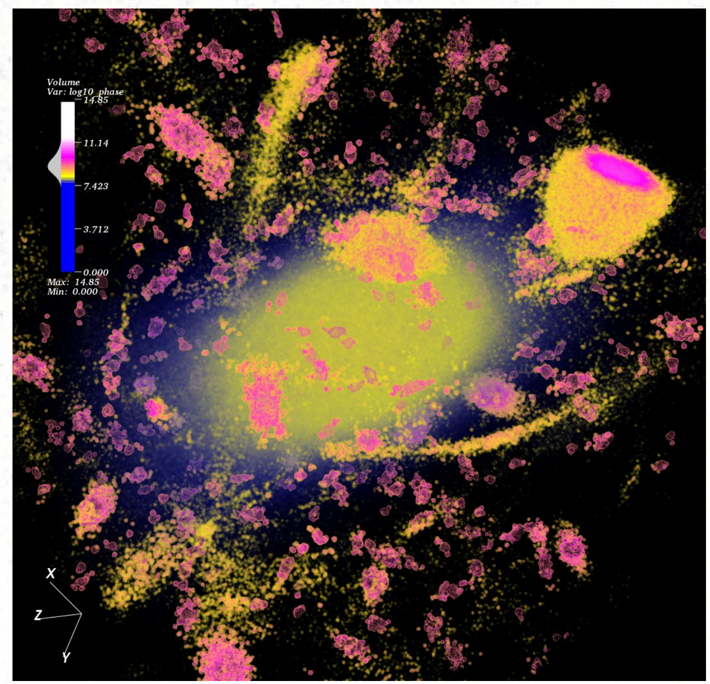
Numerical Simulations of Galactic DM Substructure And Implications for Direct and Indirect Detection

Michael Kuhlen, UC Berkeley



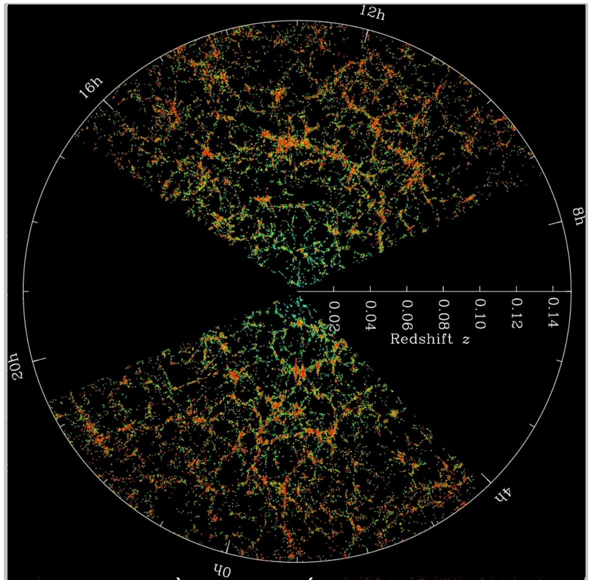


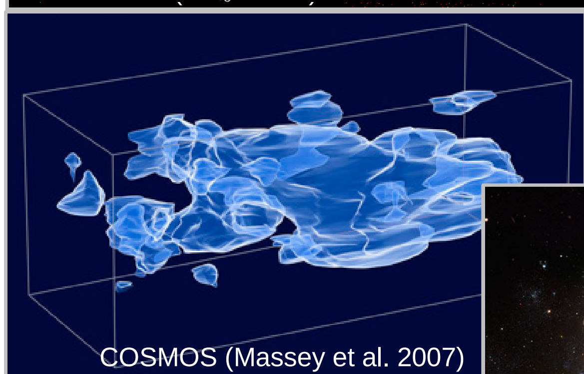


Collaborators: P. Madau (UCSC), J. Diemand (Zurich), M. Zemp (Michigan), B. Moore (Zurich), J. Stadel (Zurich), D. Potter (Zurich), N. Weiner (NYU), B. Anderson (SCIPP), R. Johnson (SCIPP), M. Kamionkowski (Caltech), S. Koushiappas (Brown)

There's evidence for dark matter on many scales...

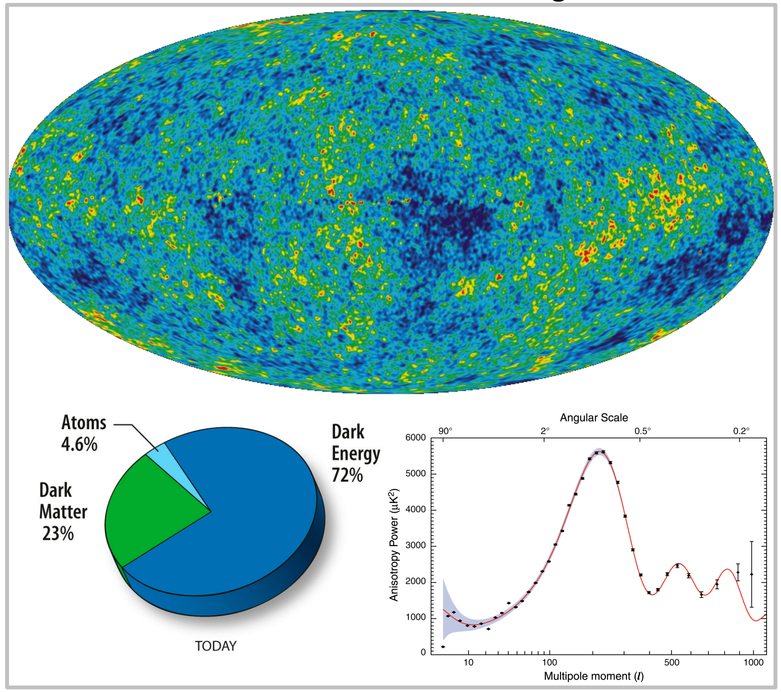
Large Scale Structure



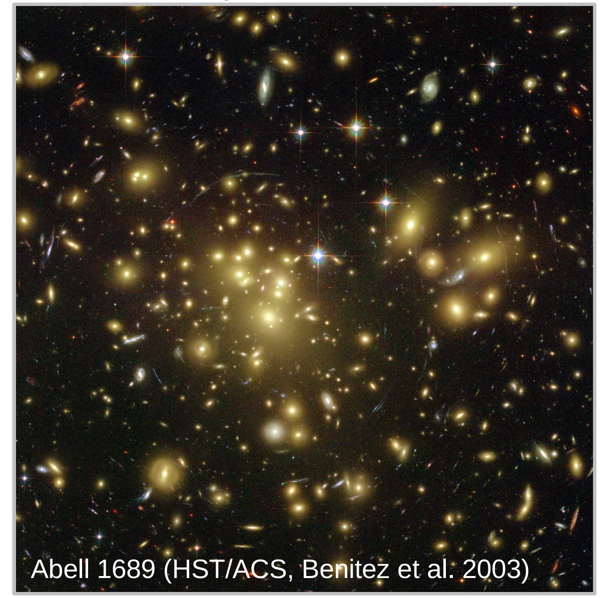


COSMOS (Massey et al. 2007)

Cosmic Microwave Background

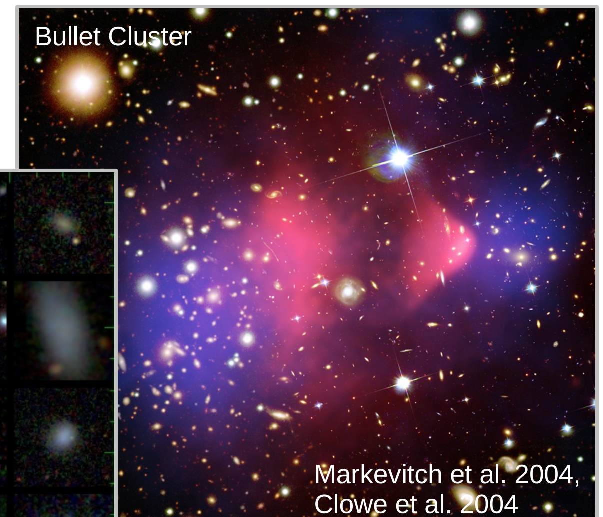


Galaxy Clusters



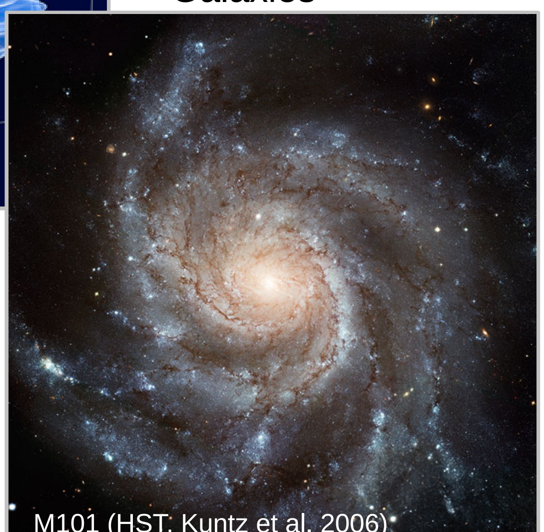
Abell 1689 (HST/ACS, Benitez et al. 2003)

Bullet Cluster



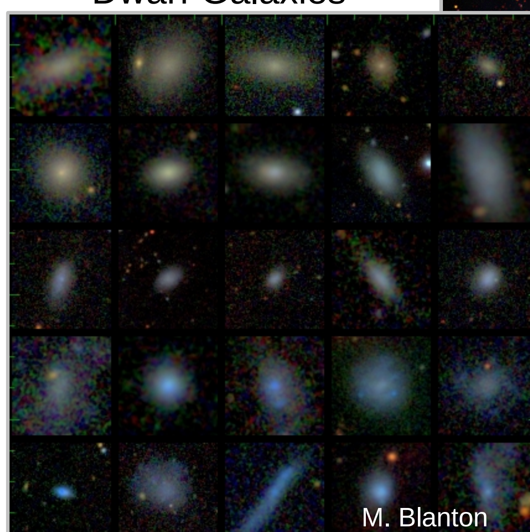
Markevitch et al. 2004, Clowe et al. 2004

Galaxies



M101 (HST; Kuntz et al. 2006)

Dwarf Galaxies

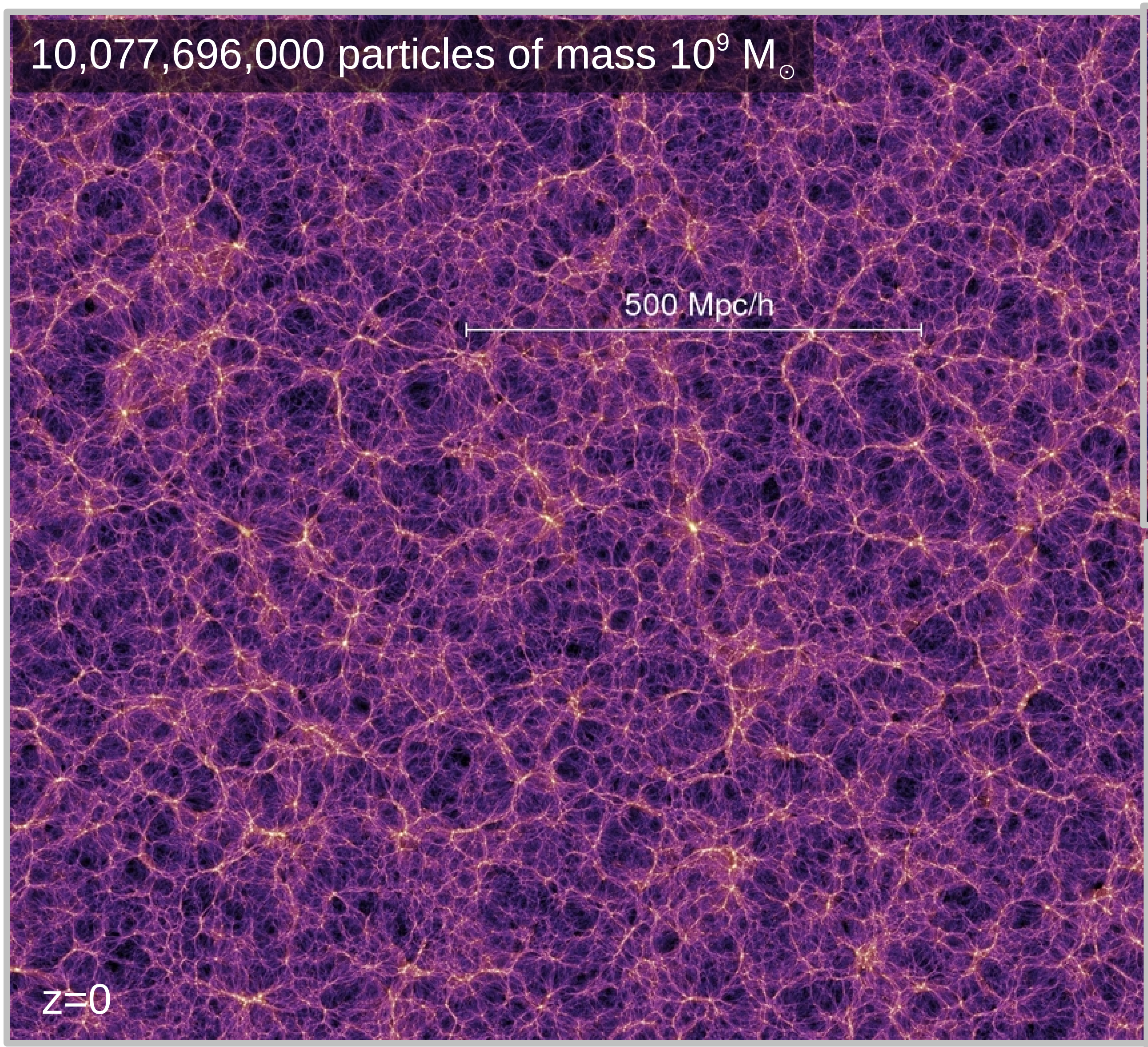


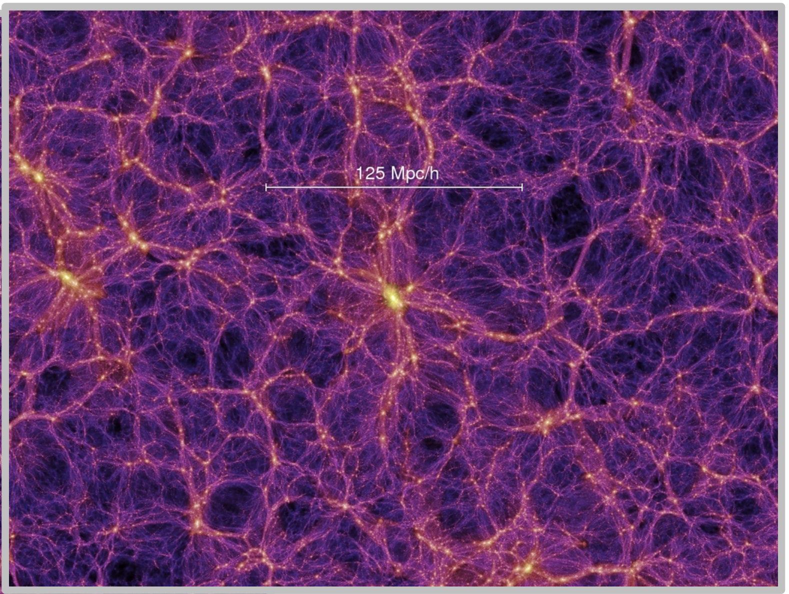
M. Blanton

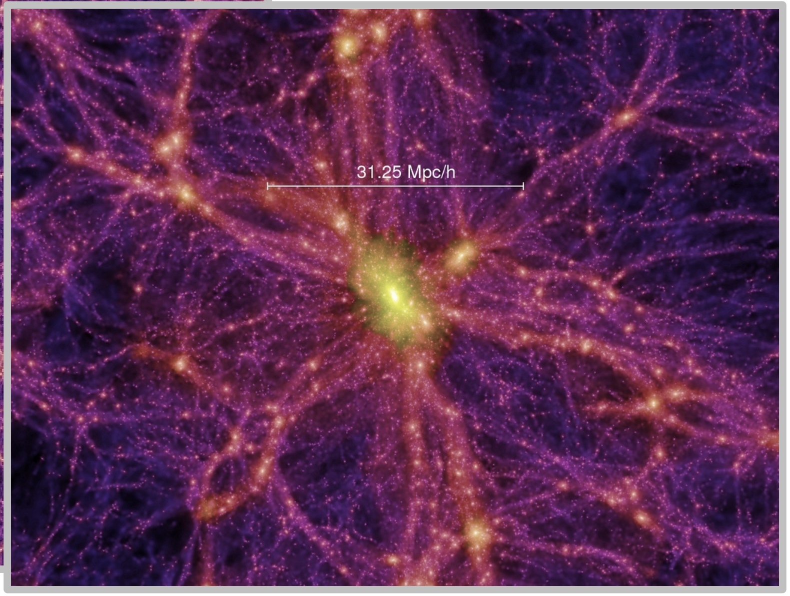
Numerical Simulations: Universe Scale

The Millenium Run (Springel et al. 2005)

Max-Planck-Institut
für Astrophysik



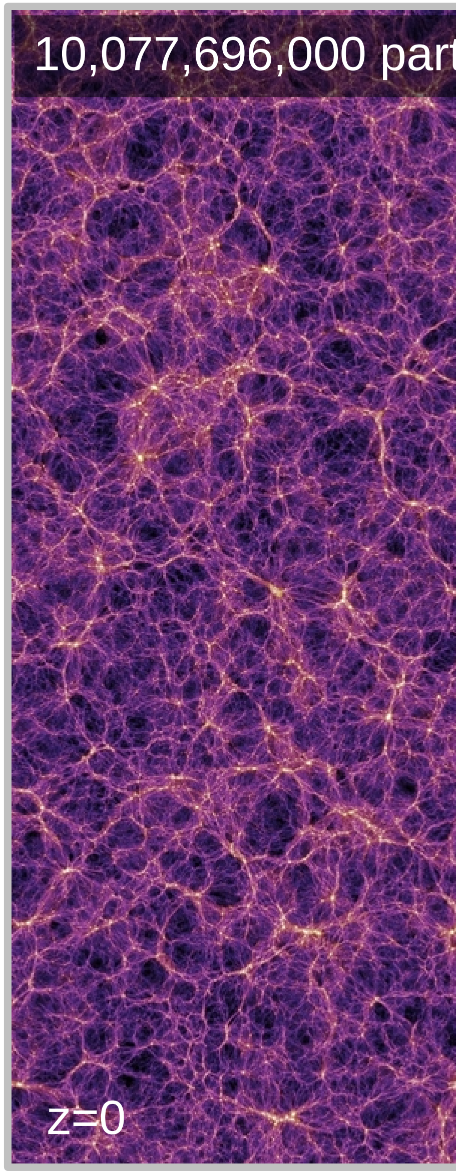


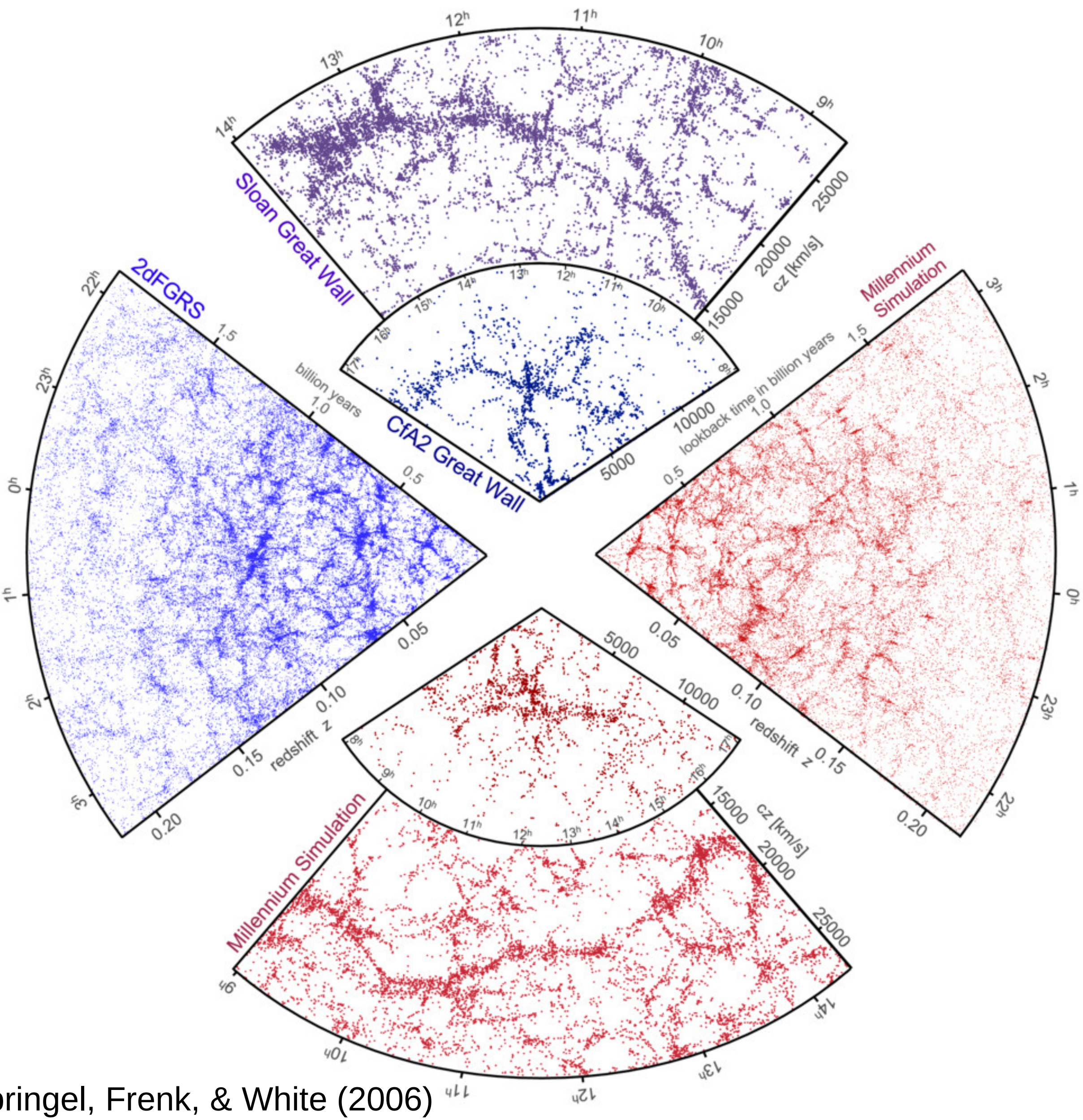


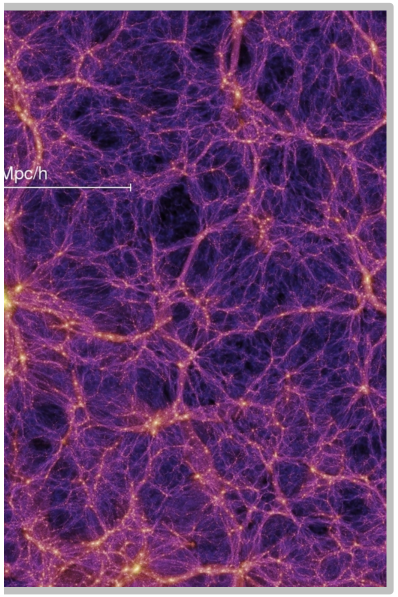
Numerical Simulations: Universe Scale

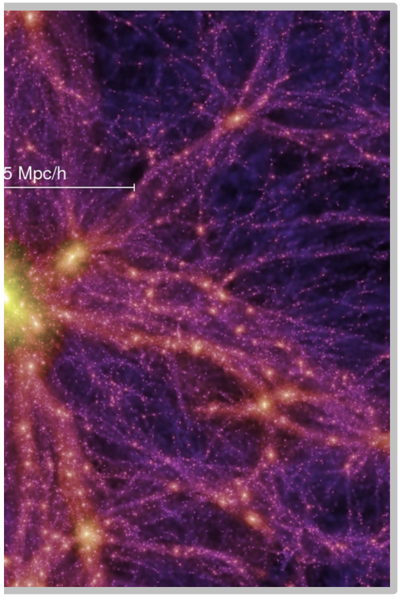
The Millenium Run (Springel et al. 2005)

Max-Planck-Institut
für Astrophysik





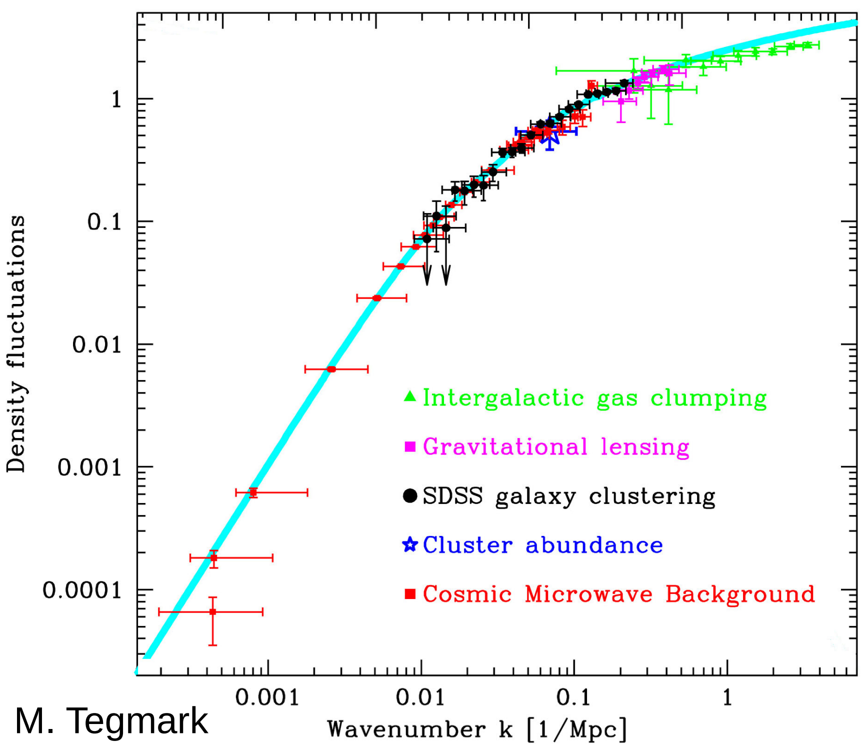




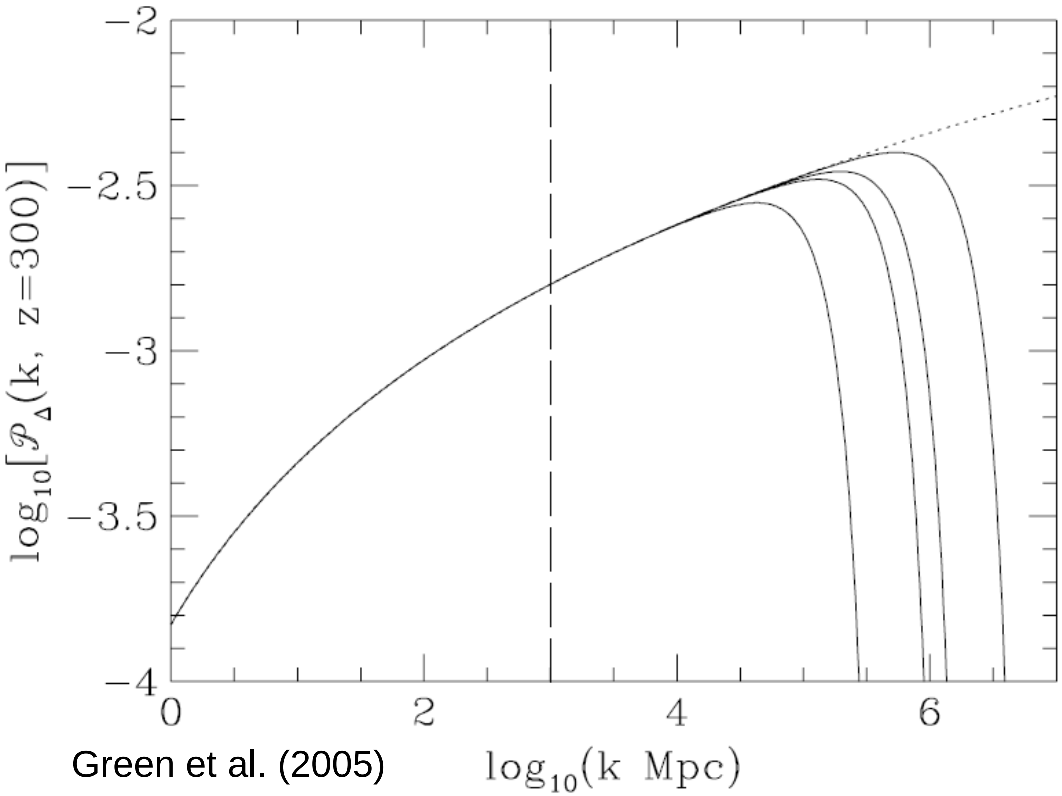
Springel, Frenk, & White (2006)

What mass are the smallest DM structures?

A cutoff in the dark matter density fluctuation power spectrum is set by collisional damping between chemical decoupling (abundance freeze-out) and kinetic decoupling (end of elastic scattering), and by free-streaming afterwards.



M. Tegmark



Green et al. (2005)

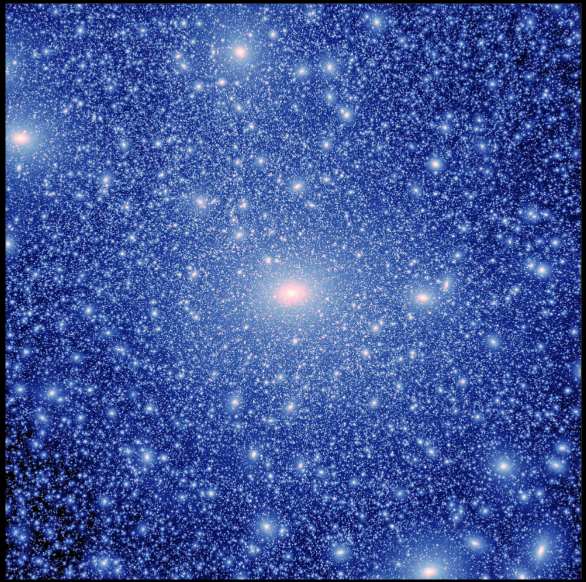
The density fluctuations on (sub-)galactic scales grow to be **strongly non-linear**. Following their evolution and dynamics accurately requires **extremely high resolution numerical simulations**.

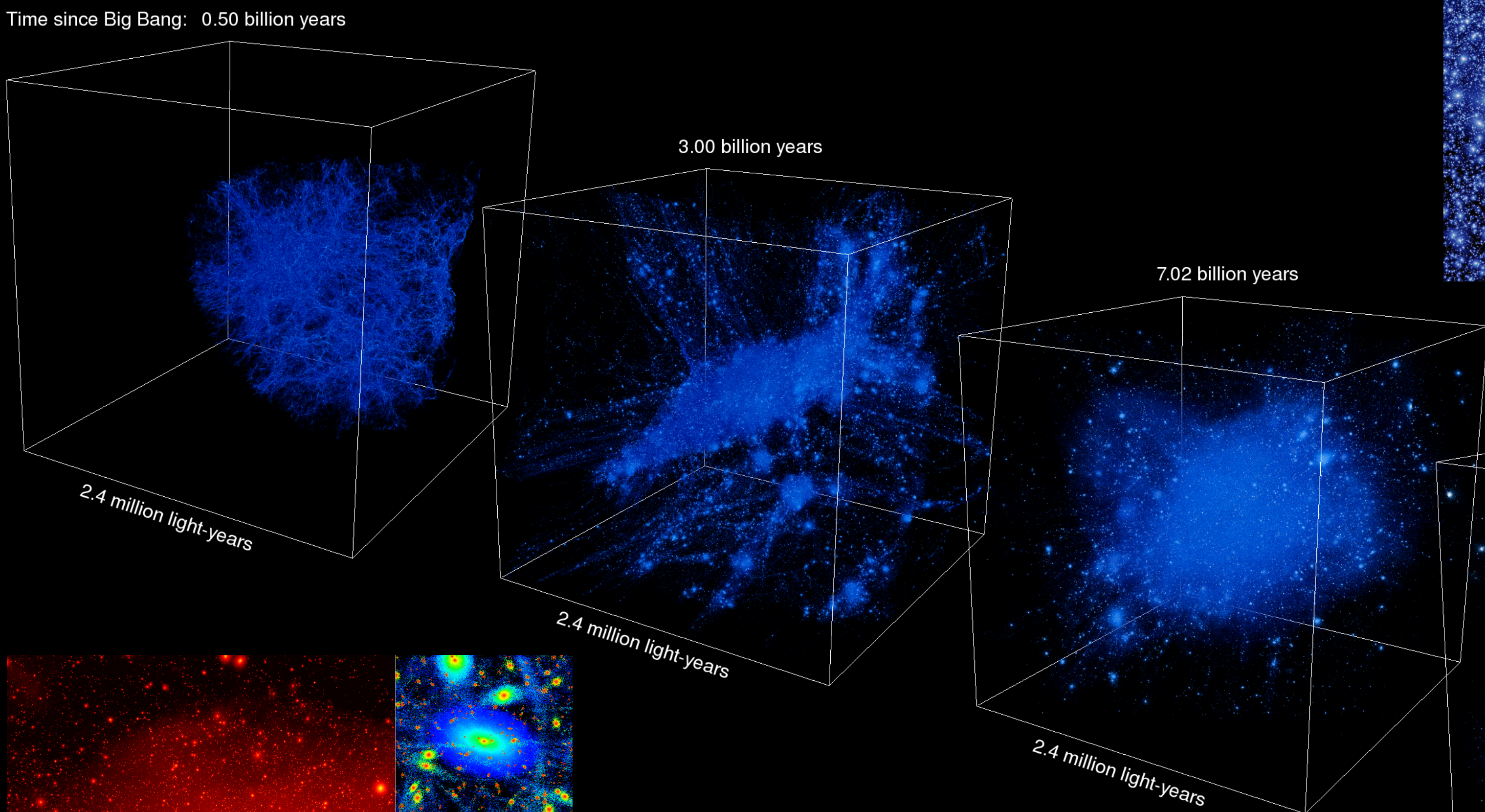
The Via Lactea Project

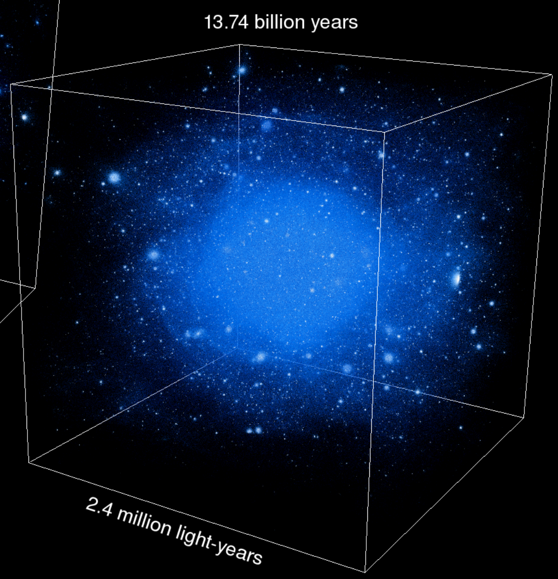
J. Diemand – M. Kuhlen – P. Madau

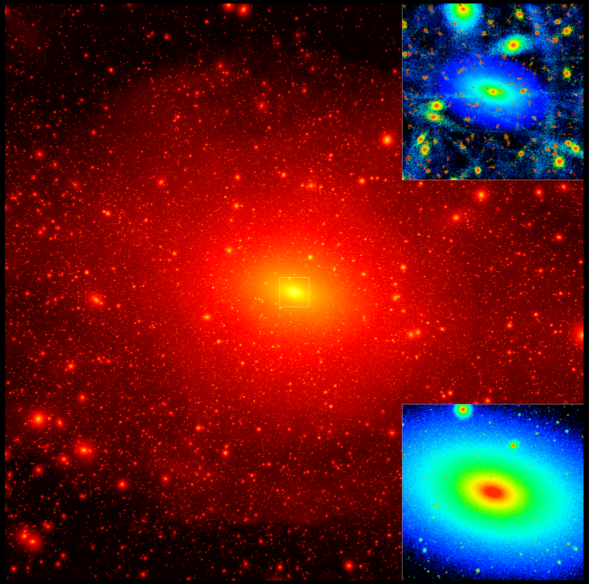
(& B. Moore, D. Potter, J. Stadel, M. Zemp)

GHALO
Stadel et al. (2009)
2.1 billion particles, 1,000 $M_\odot$









VIA LACTEA II
Diemand, Kuhlen et al. 2008
1.1 billion particles, 4,000 $M_\odot$

SciDAC
Scientific Discovery through Advanced Computing

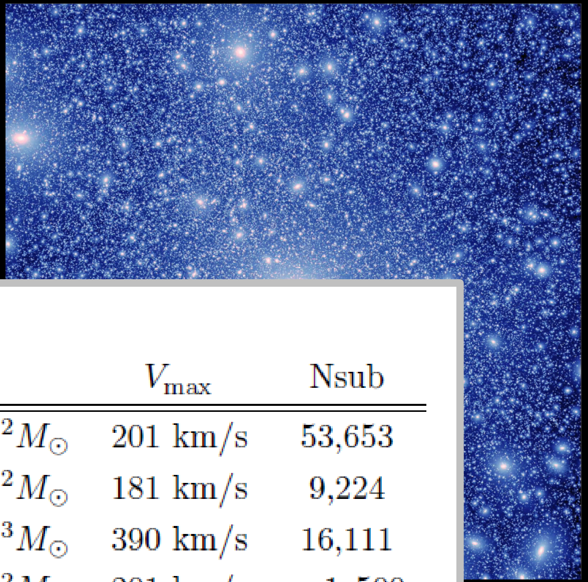
Office of Science
INCITE
Advancing America's Science and Industrial Competitiveness

The Via Lactea Project

J. Diemand – M. Kuhlen – P. Madau

(& B. Moore, D. Potter, J. Stadel, M. Zemp)

GHALO
Stadel et al. (2009)
2.1 billion particles, 1,000 $M_\odot$



Time since Big

Via Lactea Series

Name	$N_{\rm hires}$	$M_{\rm hires}$	z_i	z_f	cosmology	r_{200}	M_{200}	$V_{\rm max}$	Nsub
VL-II	1.09×10^9	$4.1 \times 10^3 M_\odot$	104.3	0	WMAP-3	402 kpc	$1.93 \times 10^{12} M_\odot$	201 km/s	53,653
VL-I	2.34×10^8	$2.1 \times 10^4 M_\odot$	48.8	0	WMAP-3	389 kpc	$1.77 \times 10^{12} M_\odot$	181 km/s	9,224
1e8Ell	1.36×10^8	$1.8 \times 10^5 M_\odot$	59.5	0.49	WMAP-1	512 kpc	$1.34 \times 10^{13} M_\odot$	390 km/s	16,111
VL-IIm	2×10^7	$2.6 \times 10^5 M_\odot$	104.3	0	WMAP-3	402 kpc	$1.93 \times 10^{12} M_\odot$	201 km/s	$\sim 1,500$

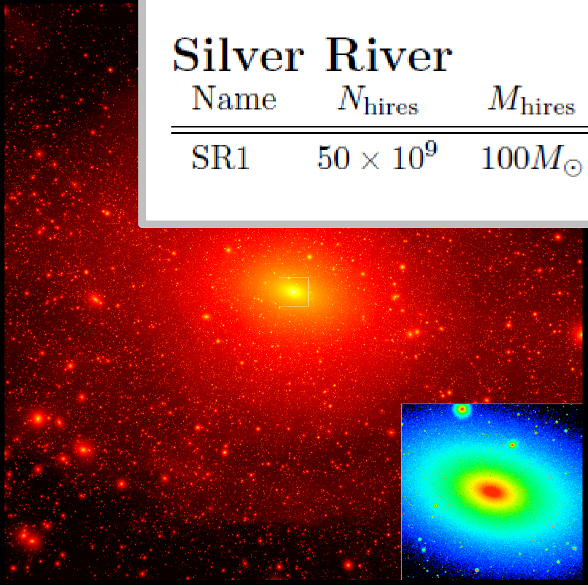
GHALO Series

Name	$N_{\rm hires}$	$M_{\rm hires}$	z_i	z_f	cosmology	r_{200}	M_{200}	$V_{\rm max}$	Nsub
$\rm GHALO_2$	2.1×10^9	$1,000 M_\odot$	48.8	0	WMAP-3	347 kpc	$1.3 \times 10^{12} M_\odot$	153 km/s	$\sim 10^5$
$\rm GHALO_3$	$\sim 10^8$	$2.7 \times 10^4 M_\odot$	48.8	0	WMAP-3	347 kpc	$1.3 \times 10^{12} M_\odot$	150 km/s	$\sim 2,500$
$\rm GHALO_4$	$\sim 5 \times 10^6$	$7.3 \times 10^5 M_\odot$	48.8	0	WMAP-3	347 kpc	$1.3 \times 10^{12} M_\odot$	150 km/s	–

Silver River

Name	$N_{\rm hires}$	$M_{\rm hires}$	z_i	z_f	cosmology	r_{200}	M_{200}	$V_{\rm max}$	Nsub
SR1	50×10^9	$100 M_\odot$	180	currently at $z = 6.3$	WMAP-7	-	-	-	-

…4 million light-years



VIA LACTEA II
Diemand, Kuhlen et al. 2008
1.1 billion particles, 4,000 $M_\odot$

SciDAC
Scientific Discovery through Advanced Computing

Office of Science
INCITE
Advancing America's Science and Industrial Competitiveness

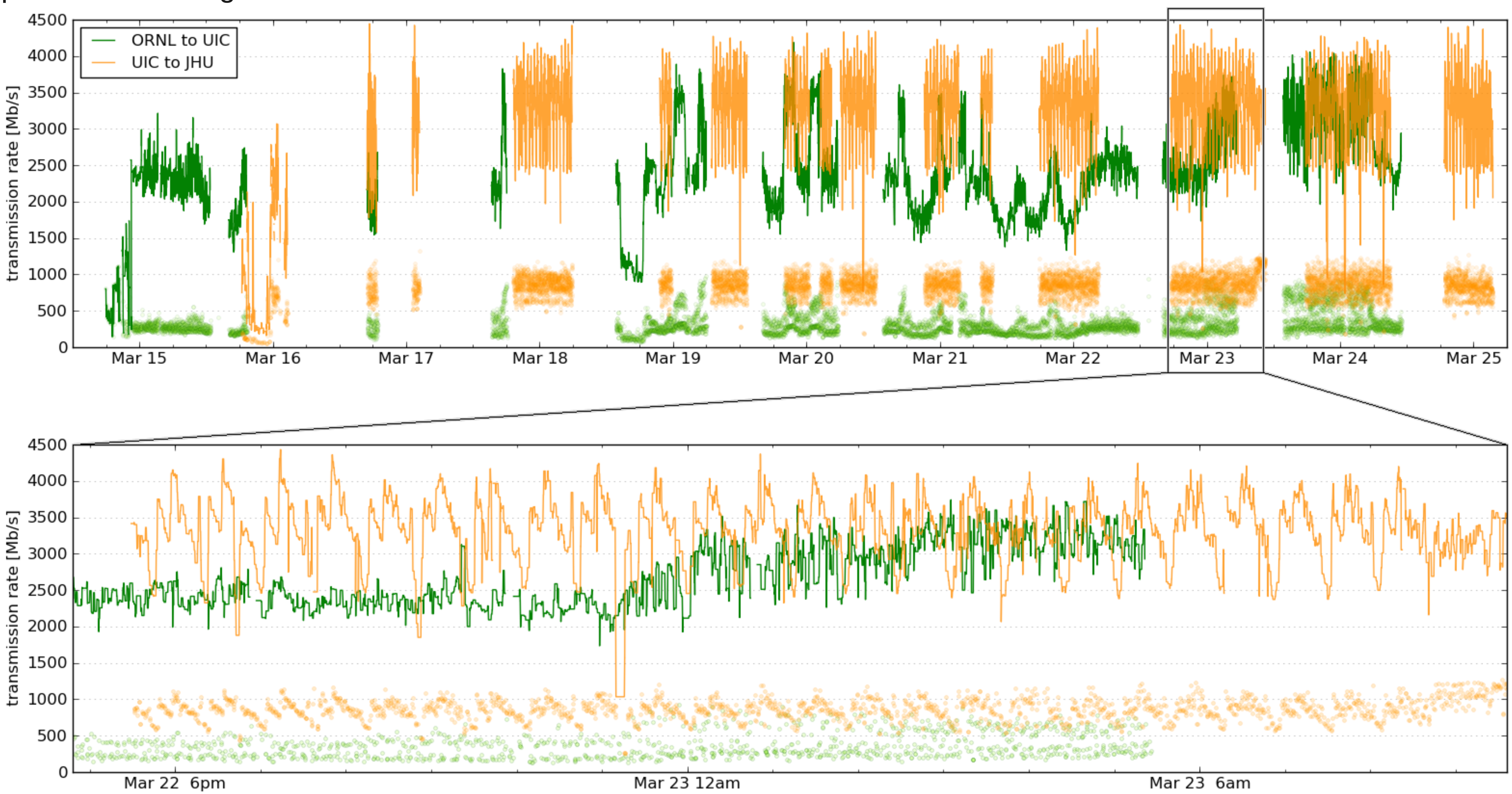
How to transfer 140 TB of data across the country

Sector – High Performance Distributed File System and Parallel Data Processing Engine
http://sector.sourceforge.net/

Yunhong Gu @ UIC

UDT – UDP-based Data Transfer
http://udt.sourceforge.net/

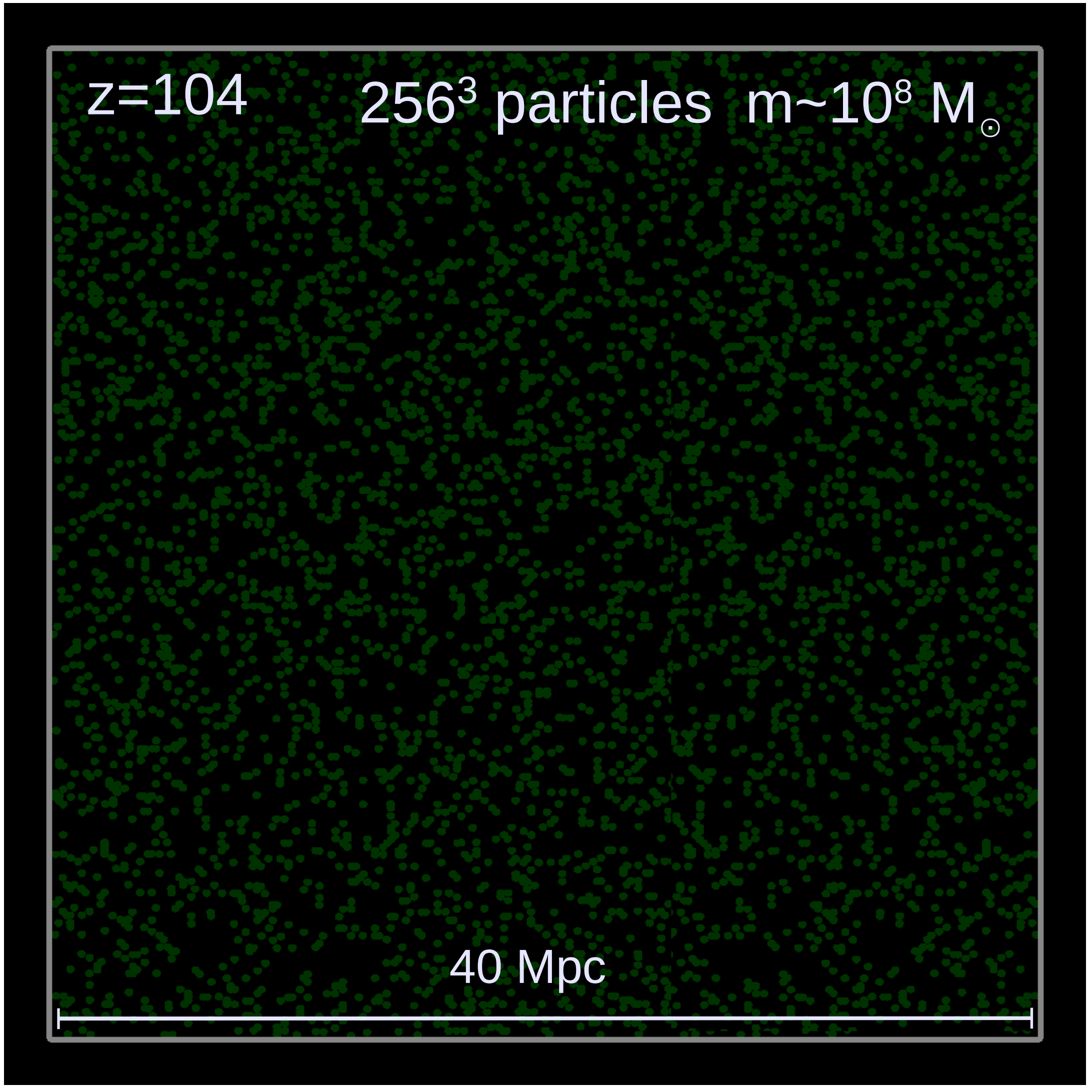
Used 10 Gbps links from ORNL to UIC and from UIC to JHU (storage server): 2500 – 3500 Mbps

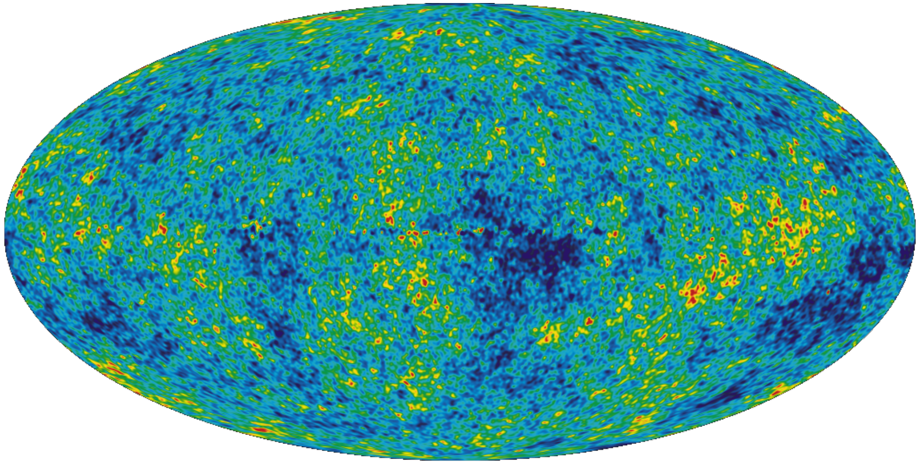


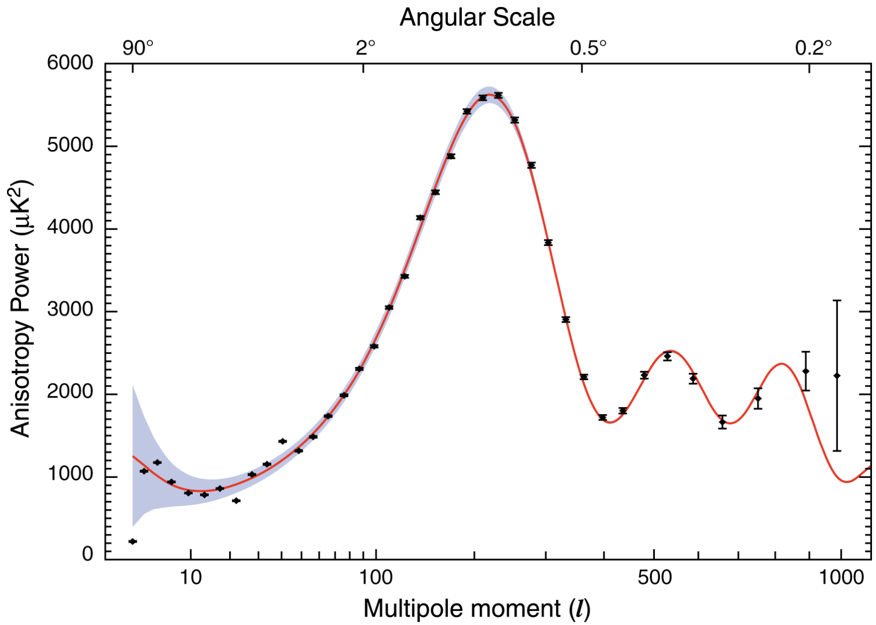
Multi-mass initial conditions

Initial conditions at redshift z=104, ~15 million years after the Big Bang.

A low resolution simulation is initialized with a Gaussian random field and a Cold Dark Matter power spectrum, normalized by CMB.

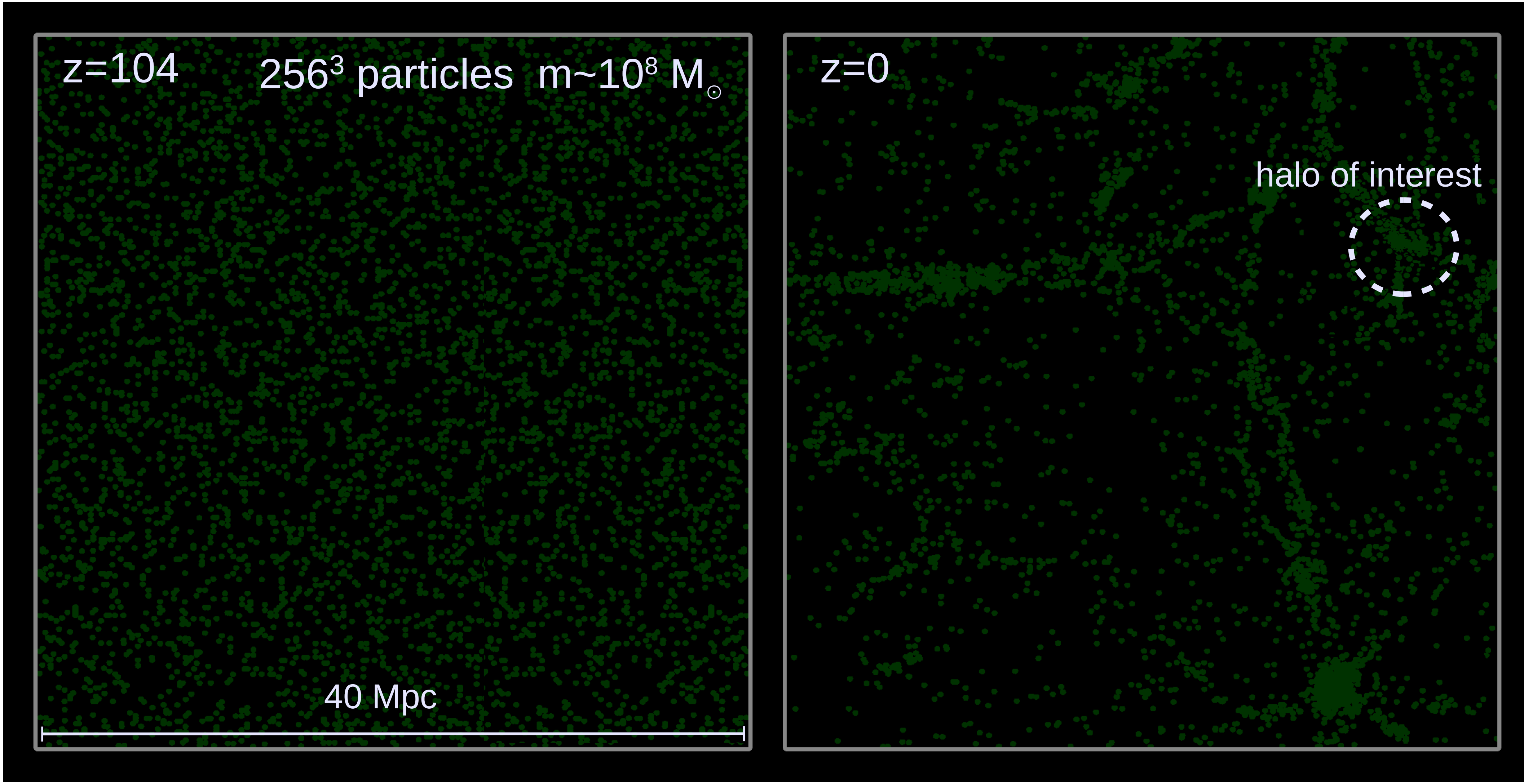






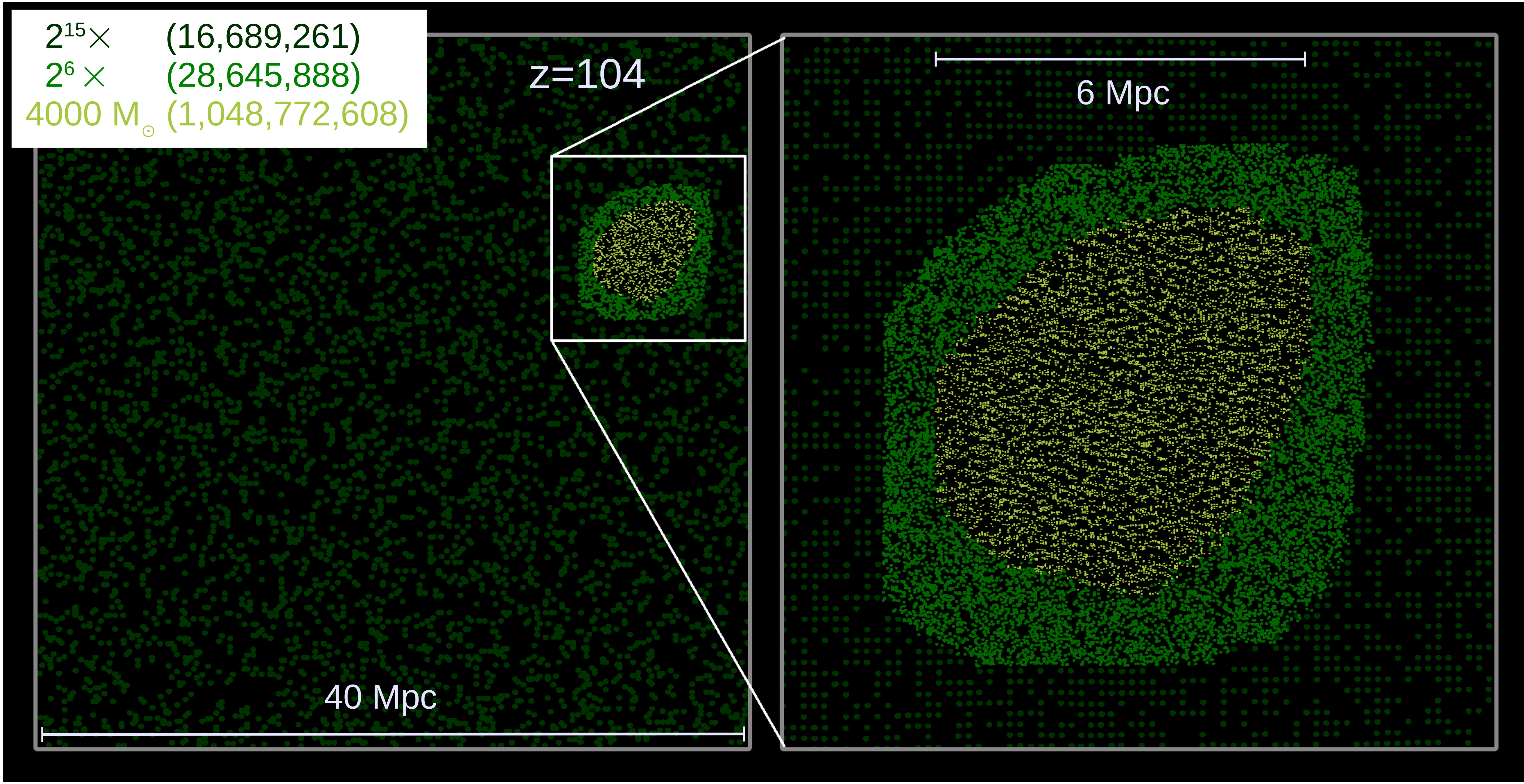
Multi-mass initial conditions

This low resolution simulation is quickly run to z=0 (13.7 billion years after the Big Bang), and a halo of interest (e.g. mass, V_{max} equal to Milky Way, no recent major mergers) is selected.



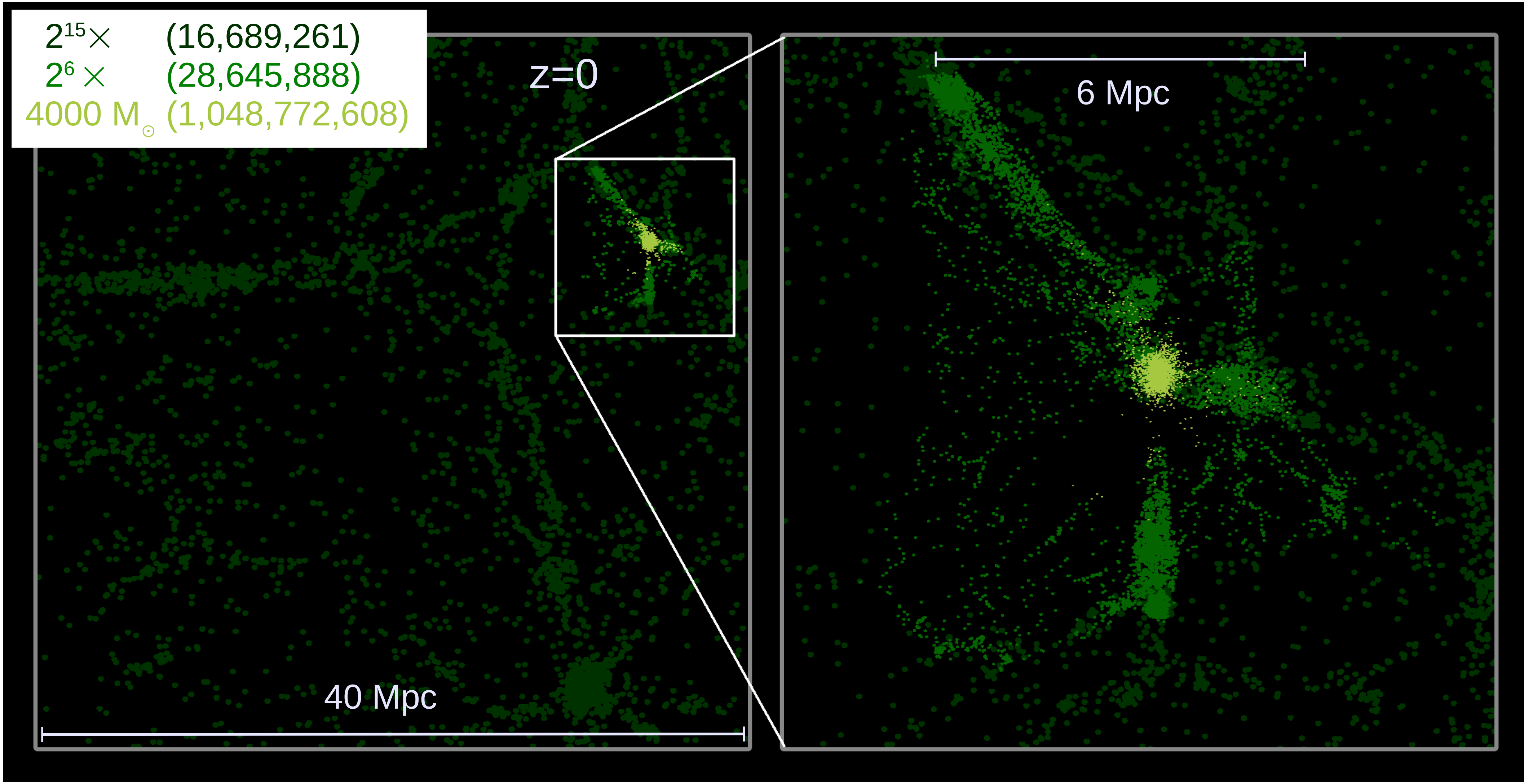
Multi-mass initial conditions

Back in the initial conditions, cover the Lagrangian volume of the halo of interest with a billion (or more) high resolution particles (yellow), which have a mass of 4,000 $M_\odot$ in VL2.



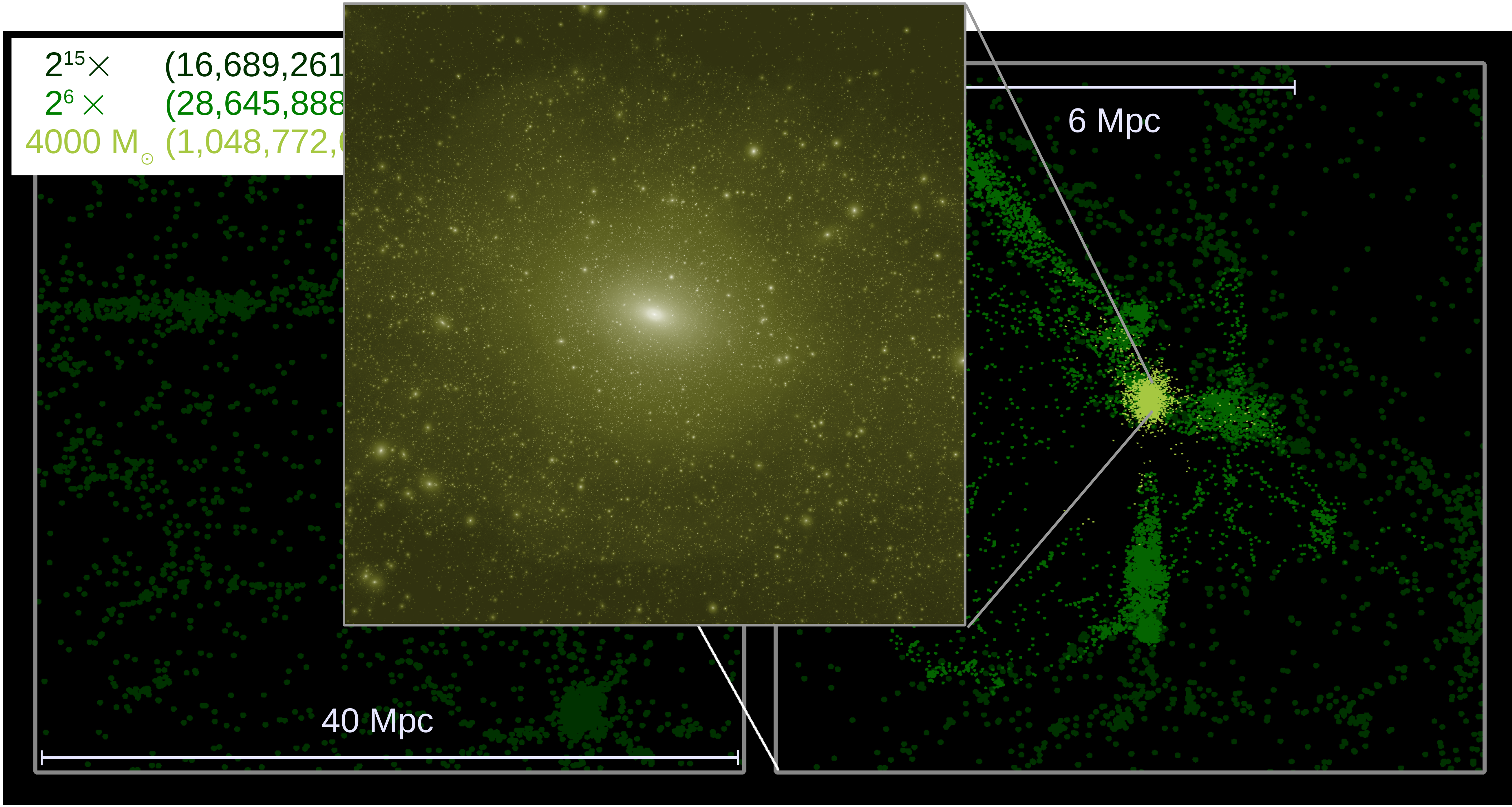
Multi-mass initial conditions

Gravity has caused the dark matter to clump. Only the region covered by high resolution particles is of interest. The low resolution particles provide the larger scale environment, e.g. the tidal field.



Multi-mass initial conditions

Gravity has caused the dark matter to clump. Only the region covered by high resolution particles is of interest. The low resolution particles provide the larger scale environment, e.g. the tidal field.



PKDGRAV – a hierarchical n-body tree code

Written by Joachim Stadel (U. Zurich) and Tom Quinn (U. Washington)

Newton's equations of motion in co-moving coordinates

$$\frac{\mathrm{d}\vec{x}}{\mathrm{d}t} = \vec{v}$$

$$\frac{\mathrm{d}\vec{v}}{\mathrm{d}t} + 2H(a)\vec{v} = -\frac{1}{a^2}\vec{\nabla}\phi.$$

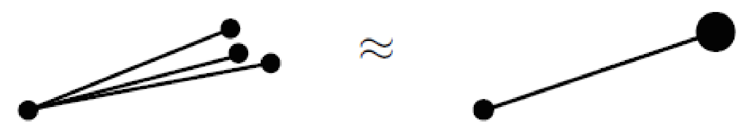
Cosmology, the expansion of the universe

$$H(a) = \dot{a}/a \quad \text{(Hubble constant)}$$

$$\frac{\ddot{a}}{a} = -\frac{4}{3}\pi G\rho_b(t) + \frac{\Lambda}{3} \quad \text{(2}^{\text{nd}}\text{ Friedman equation)}$$

Gravitational potential

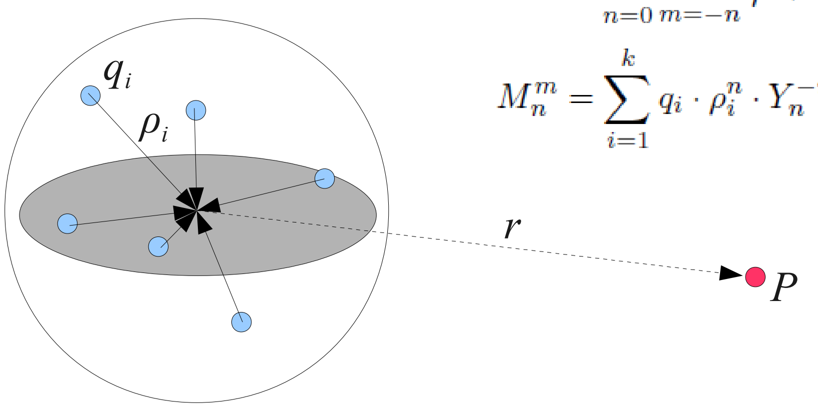
$$\nabla^2\phi = 4\pi G\rho a^2 - \Lambda a^2 + 3a\ddot{a}$$
$$= 4\pi G(\rho - \rho_b)a^2$$



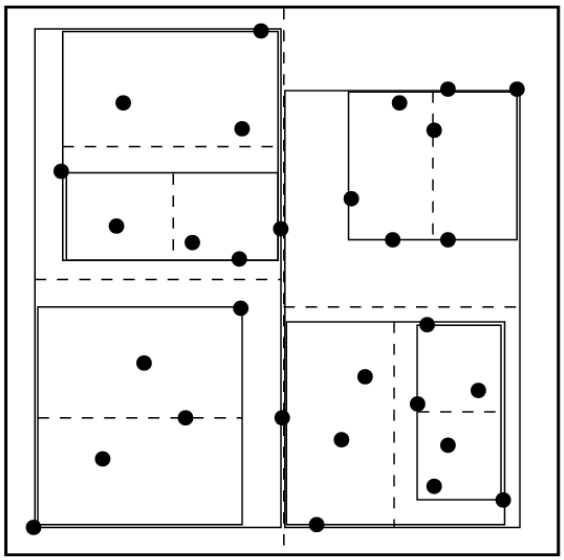
The exact spatial configuration of distant sources is unimportant. Can use a **multipole expansion of the potential** instead.

$$\phi(P) = \sum_{n=0}^{\infty}\sum_{m=-n}^{n}\frac{M_n^m}{r^{n+1}}\cdot Y_n^m(\theta,\phi)$$

$$M_n^m = \sum_{i=1}^{k} q_i\cdot\rho_i^n\cdot Y_n^{-m}(\alpha_i,\beta_i)$$



Spatially bisected binary tree:
gravity calculation $O(N^2) \rightarrow O(N \log N)$

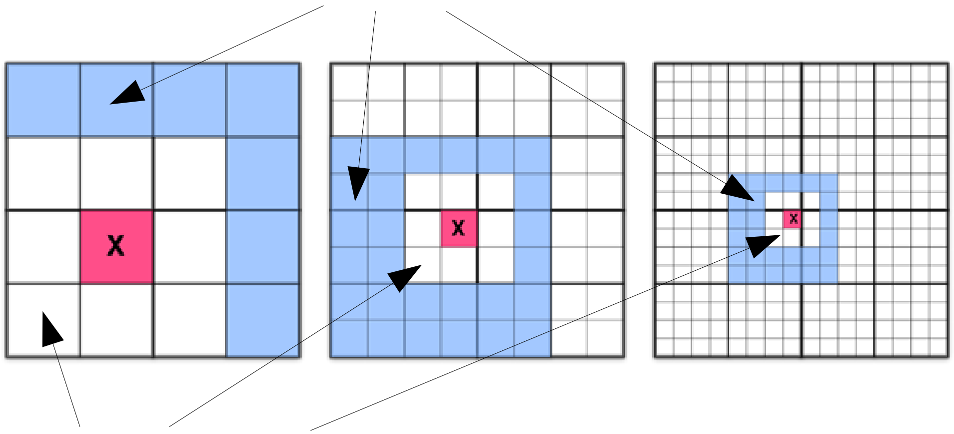


Fast Multipole Method: O(N logN) ➞ O(N)

Algorithm: Greengard & Rohklin (1985)

“A short course in fast multipole methods” by Beatson & Greengard (1997)
“An overview of fast multipole methods” by Ihler (2004)

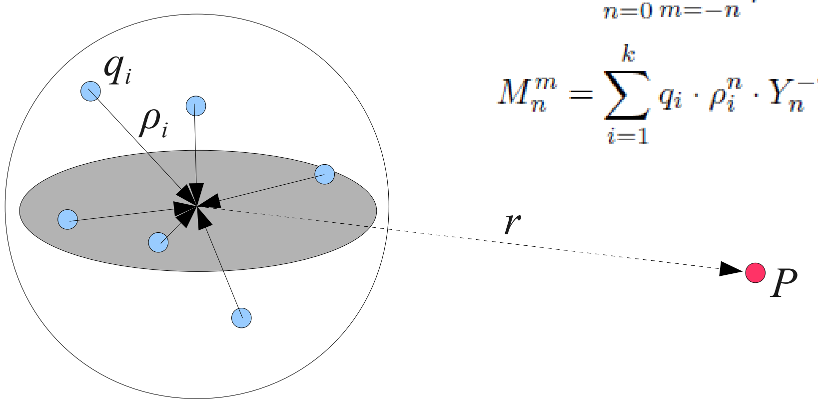
Interaction list
use multipole expansion

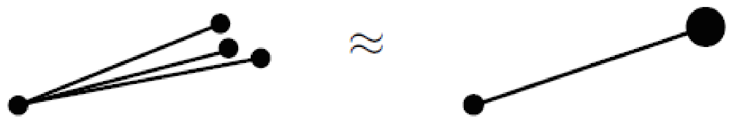


Near neighbors
evaluate at lower level,
$O(N^2)$ direct summation at finest level.

$$\phi(P) = \sum_{n=0}^{\infty} \sum_{m=-n}^{n} \frac{M_n^m}{r^{n+1}} \cdot Y_n^m(\theta, \phi)$$

$$M_n^m = \sum_{i=1}^{k} q_i \cdot \rho_i^n \cdot Y_n^{-m}(\alpha_i, \beta_i)$$





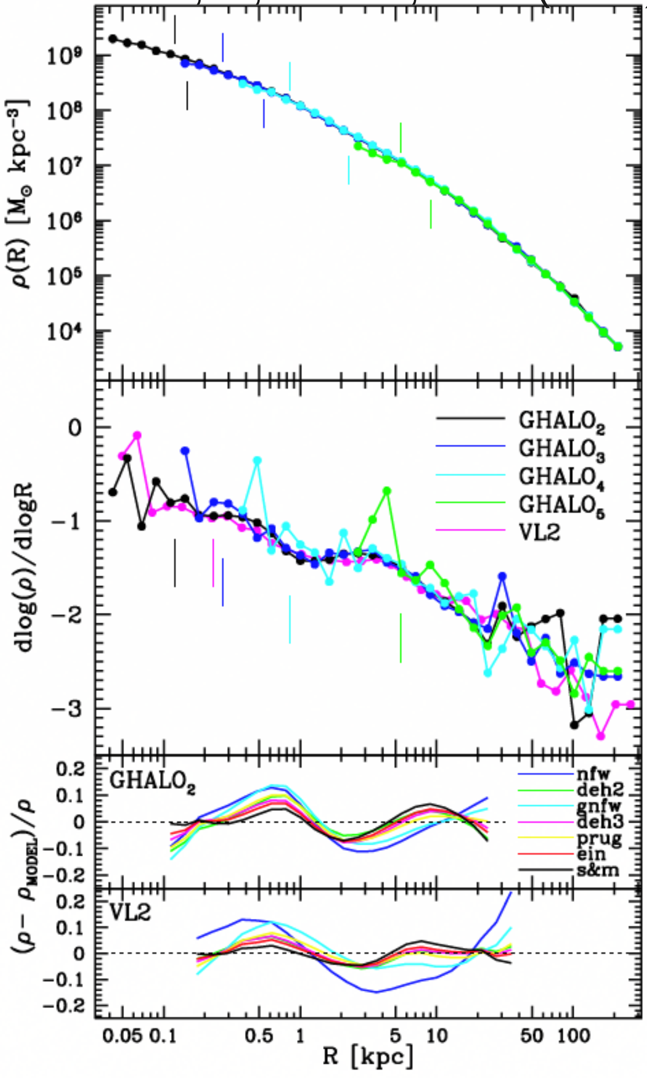
The exact spatial configuration of distant sources is unimportant. Can use a **multipole expansion of the potential** instead.

A regular tree code (e.g. Barnes & Hut) is **O(N logN), because every particle (N) is visited at every level (logN)** in order to construct and evaluate the multipole expansion.

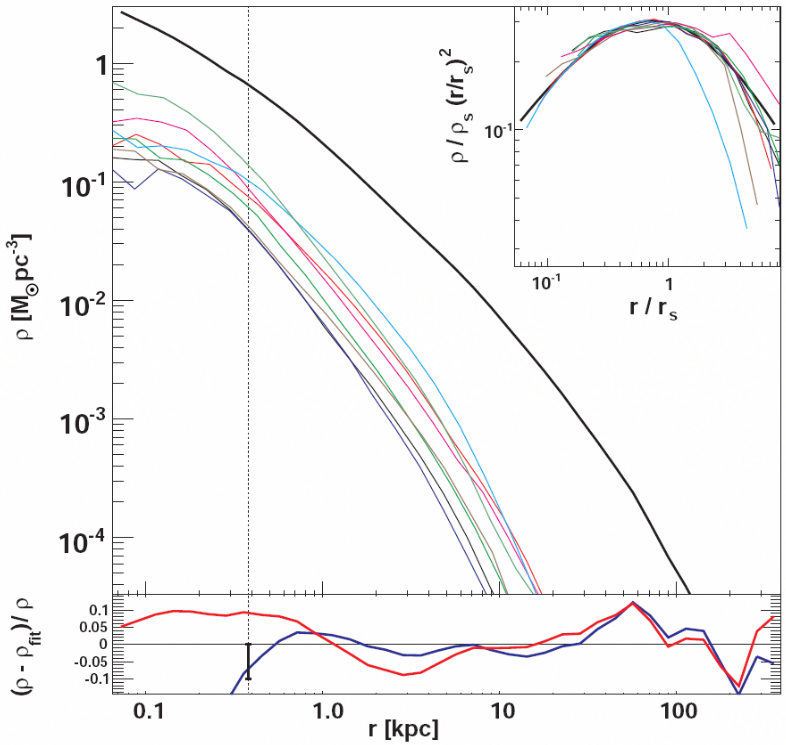
In the **Fast Multipole Method**, on every level **only every cell is visited once**, in order to construct a single expansion for the potential from all particles outside a cell's near neighbors. **O(N)**

Dark Matter Halos Are "Cuspy"

Stadel, ..., Kuhlen, et al. (2009)



Diemand, Kuhlen, et al. (2008)



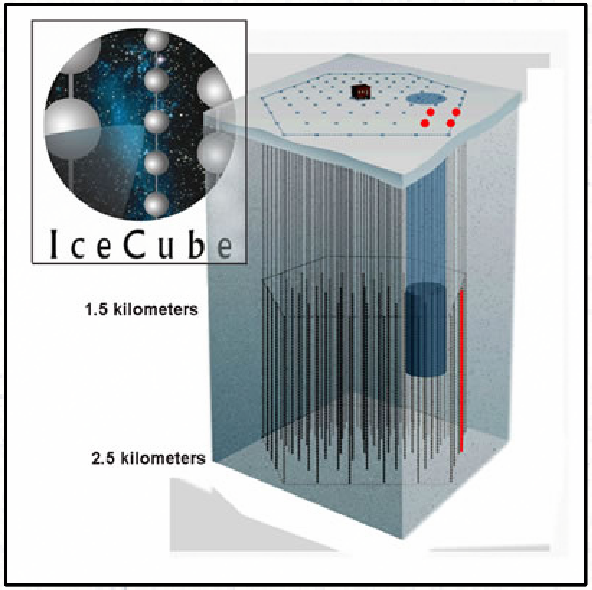
The host halo and the subhalos exhibit a "universal" density profile.

- Steep outer slope: $\rho \sim r^{-\gamma} \quad \gamma \simeq 3-4$
- Rolls over to isothermal slope: $\gamma = 2$
- Continues to become shallower, but remains cuspy $\gamma \simeq 0.8$ as far in as simulations can resolve.

Substructure Relevance for Indirect Detection

Gamma-rays
(Fermi, A.C.T.'s)

Neutrinos
(e.g. IceCube)

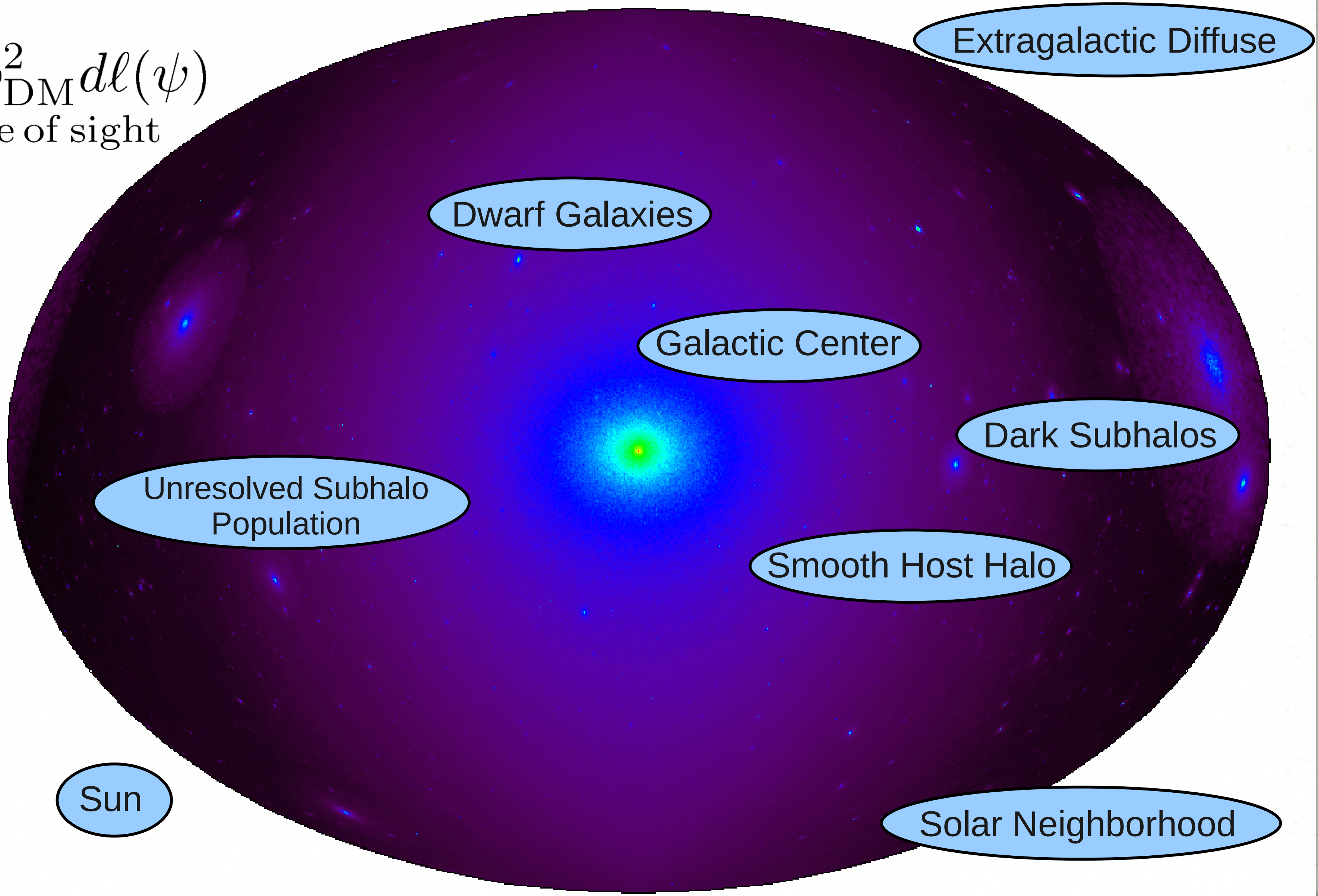


Positrons/Anti-protons
(e.g. Pamela)

$$N_\gamma = \left[\int_{\text{line of sight}} \rho_{\rm DM}^2 \, dl(\psi)\right] \frac{\langle \sigma v \rangle}{2M_\chi^2} \left[\int_{E_{th}}^{M_\chi} \left(\frac{dN_\gamma}{dE}\right) A_{\rm eff}(E) dE\right] \frac{\Delta\Omega}{4\pi} \tau_{\rm exp}$$

Substructure Relevance for Indirect Detection

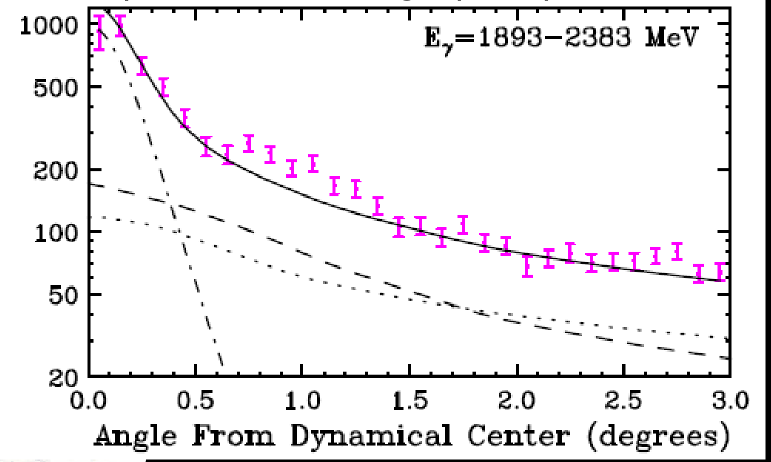
$$\int_{\text{line of sight}} \rho^2_{\text{DM}} \, d\ell(\psi)$$



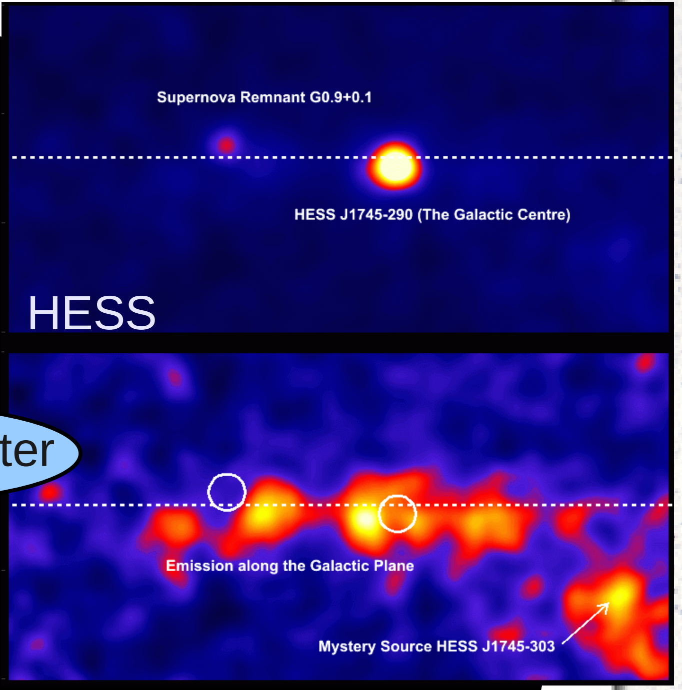
Kuhlen, Diemand, & Madau (2008)

Substructure Relevance for Indirect Detection

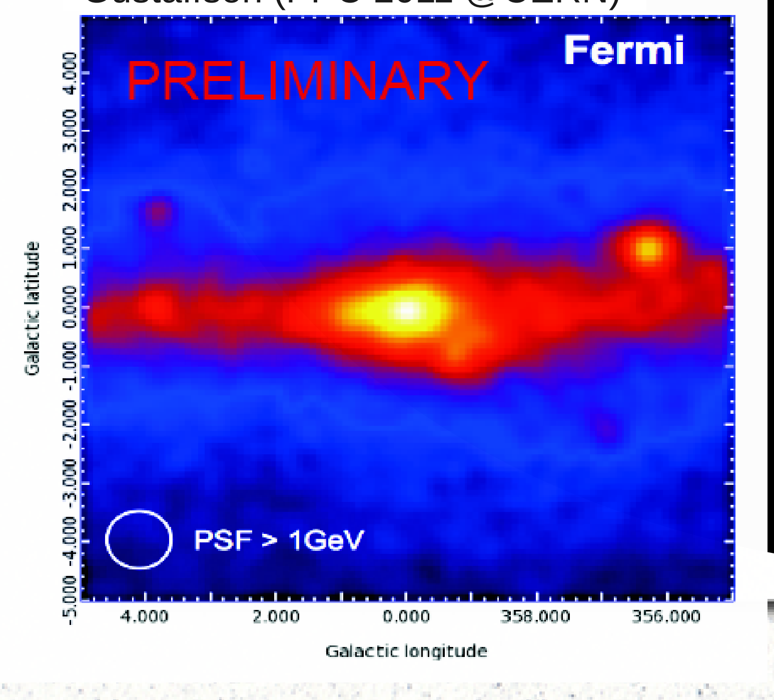
Hooper & Goodenough (2010)



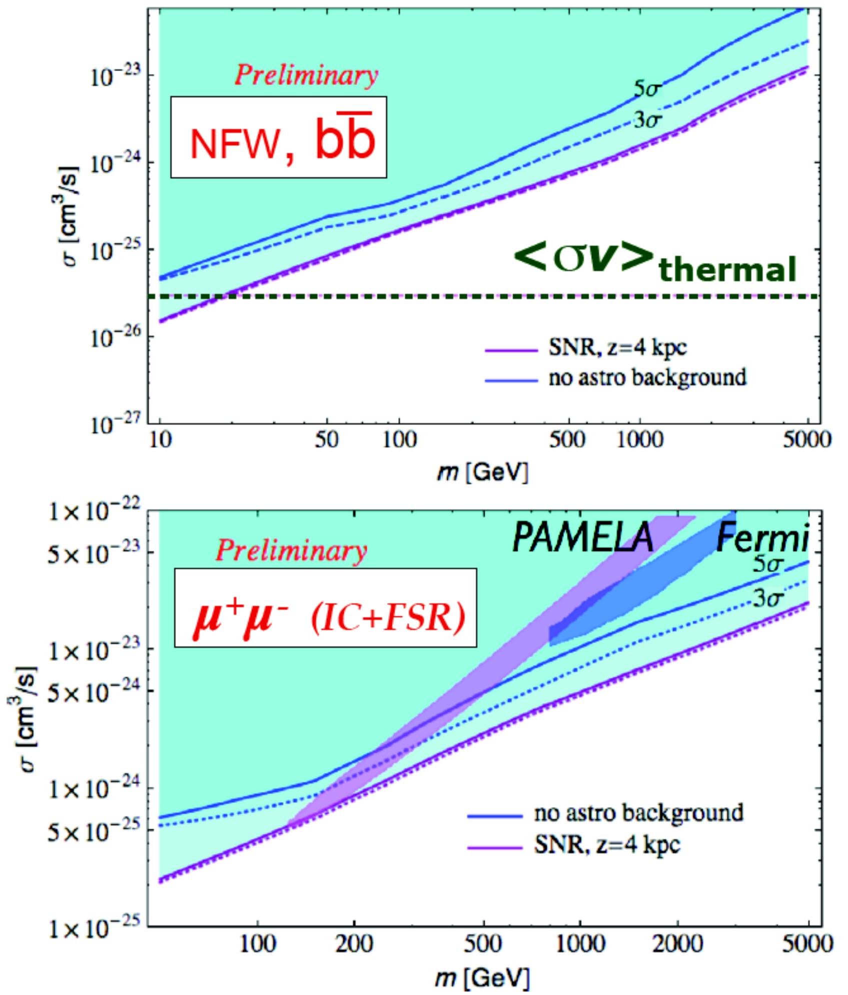
Galactic Center



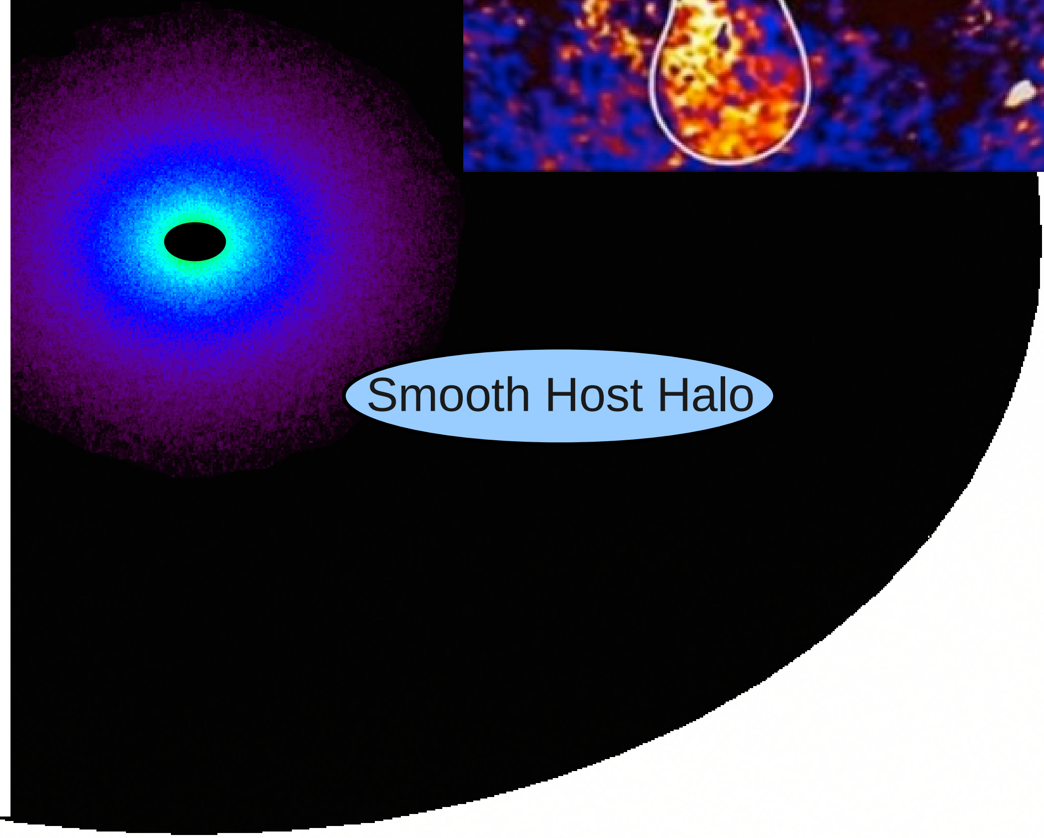
Gustaffson (PPC 2011 @CERN)

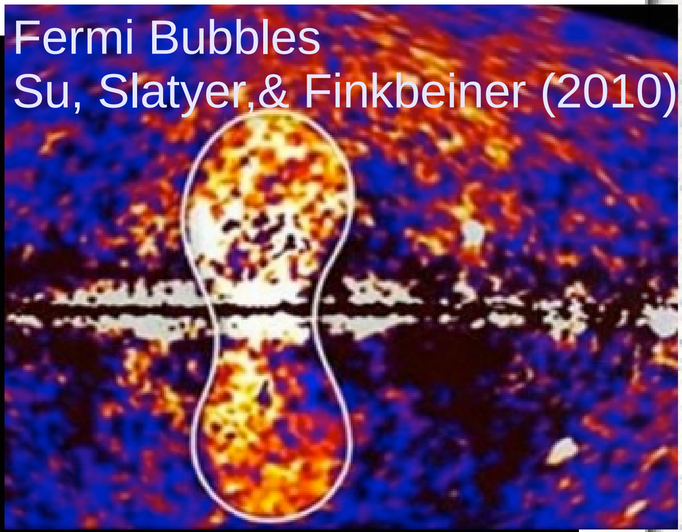


Substructure Relevance for Indirect Detection

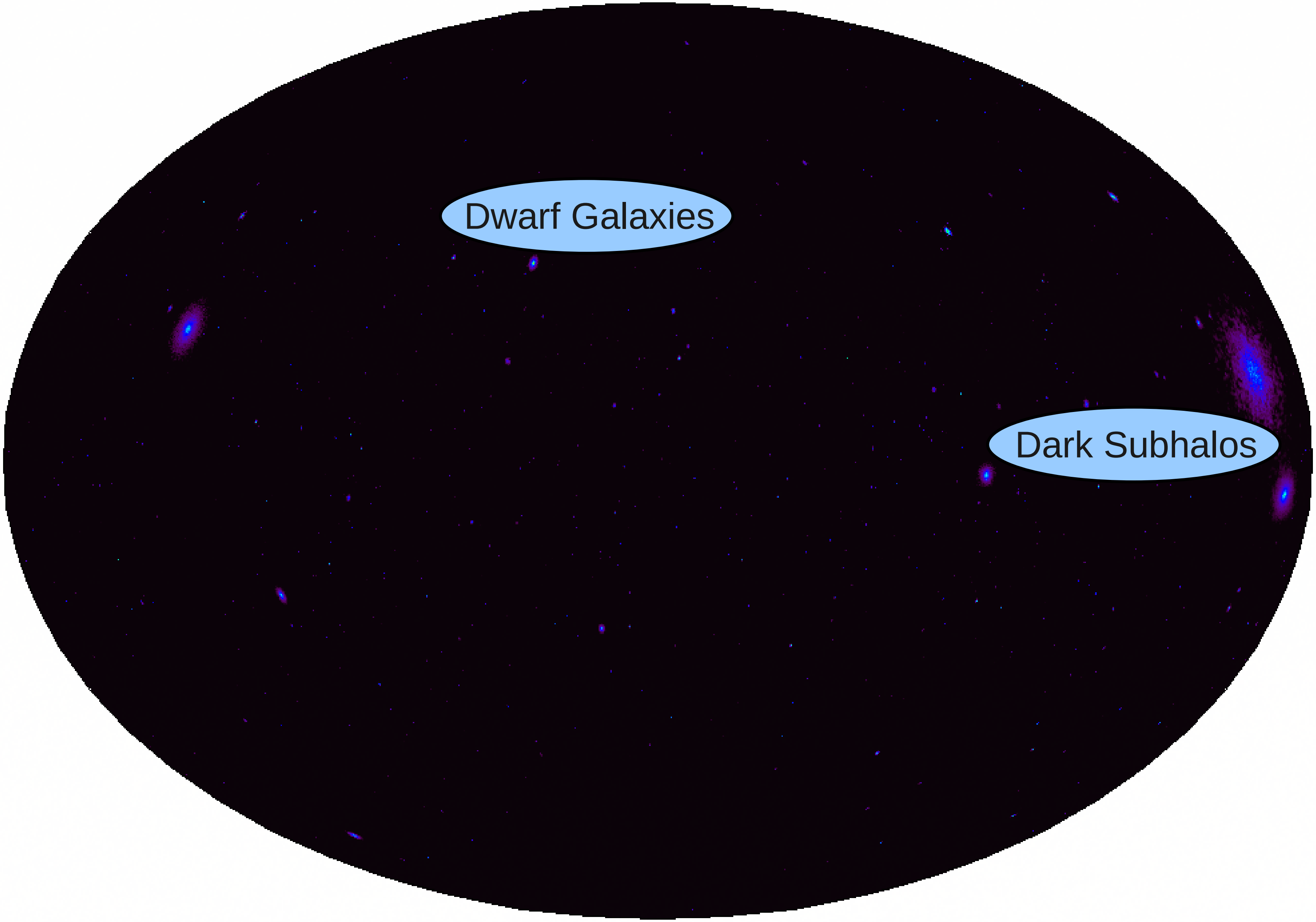


Gustaffson (PPC 2011 @CERN)

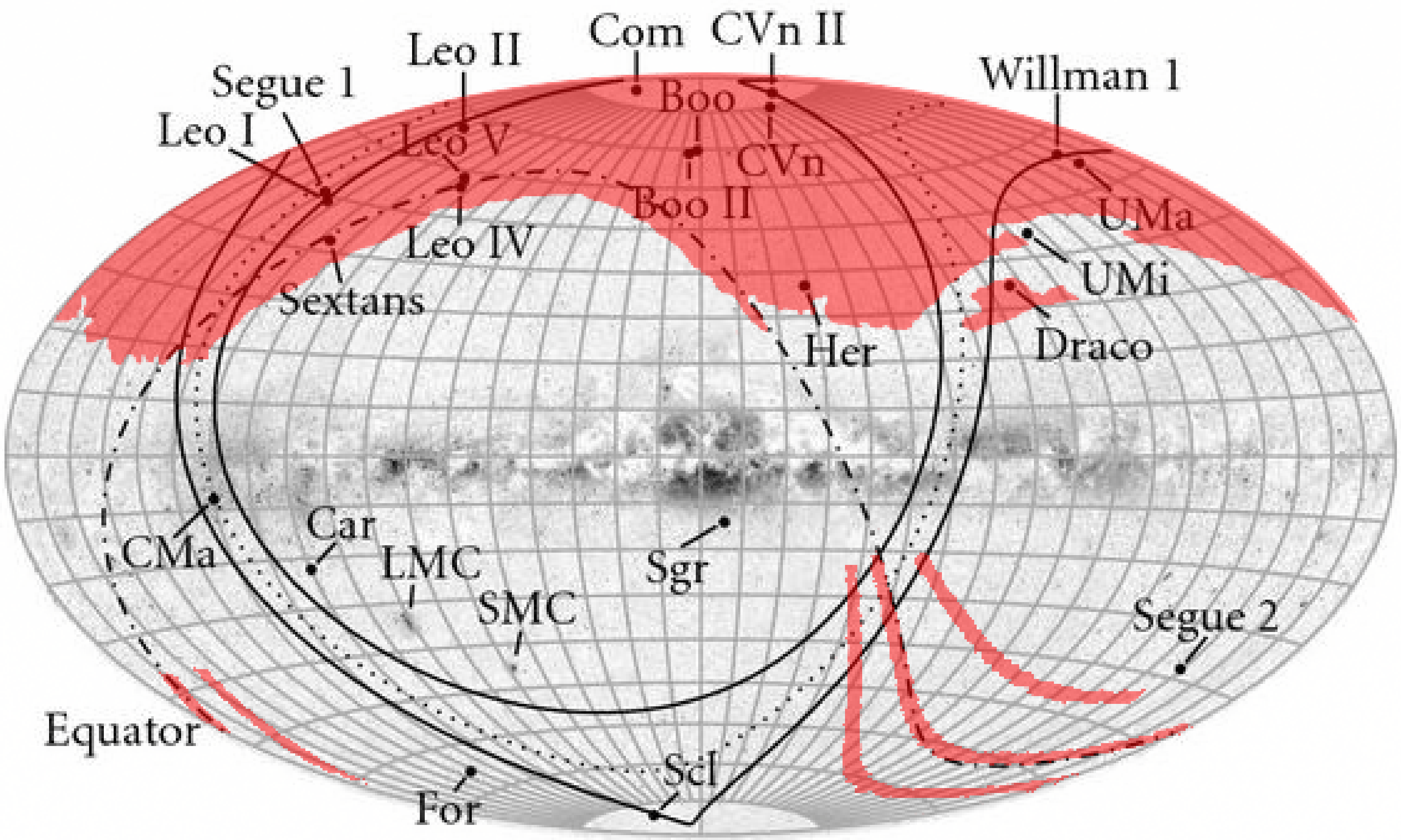




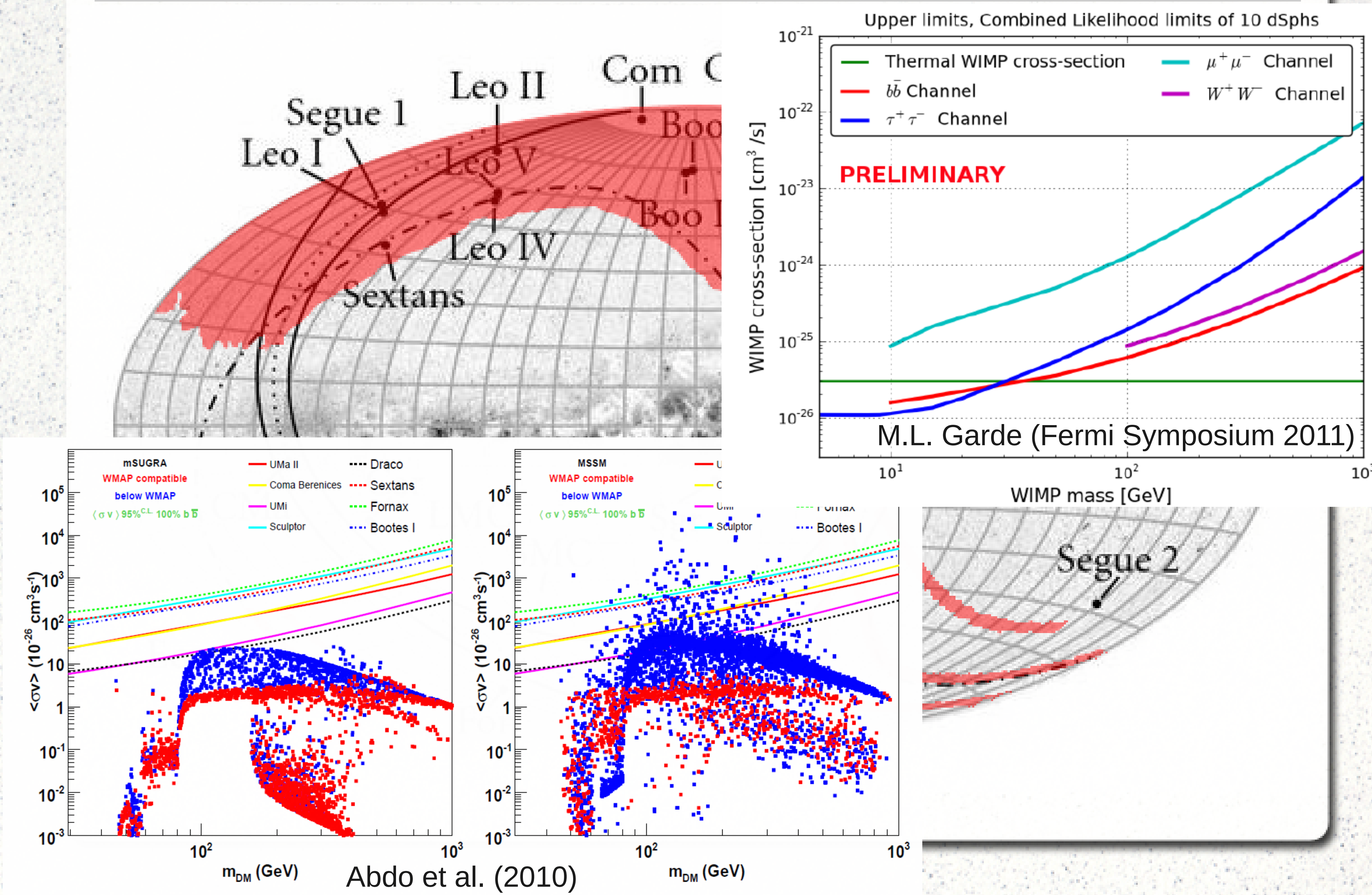
Substructure Relevance for Indirect Detection



Substructure Relevance for Indirect Detection



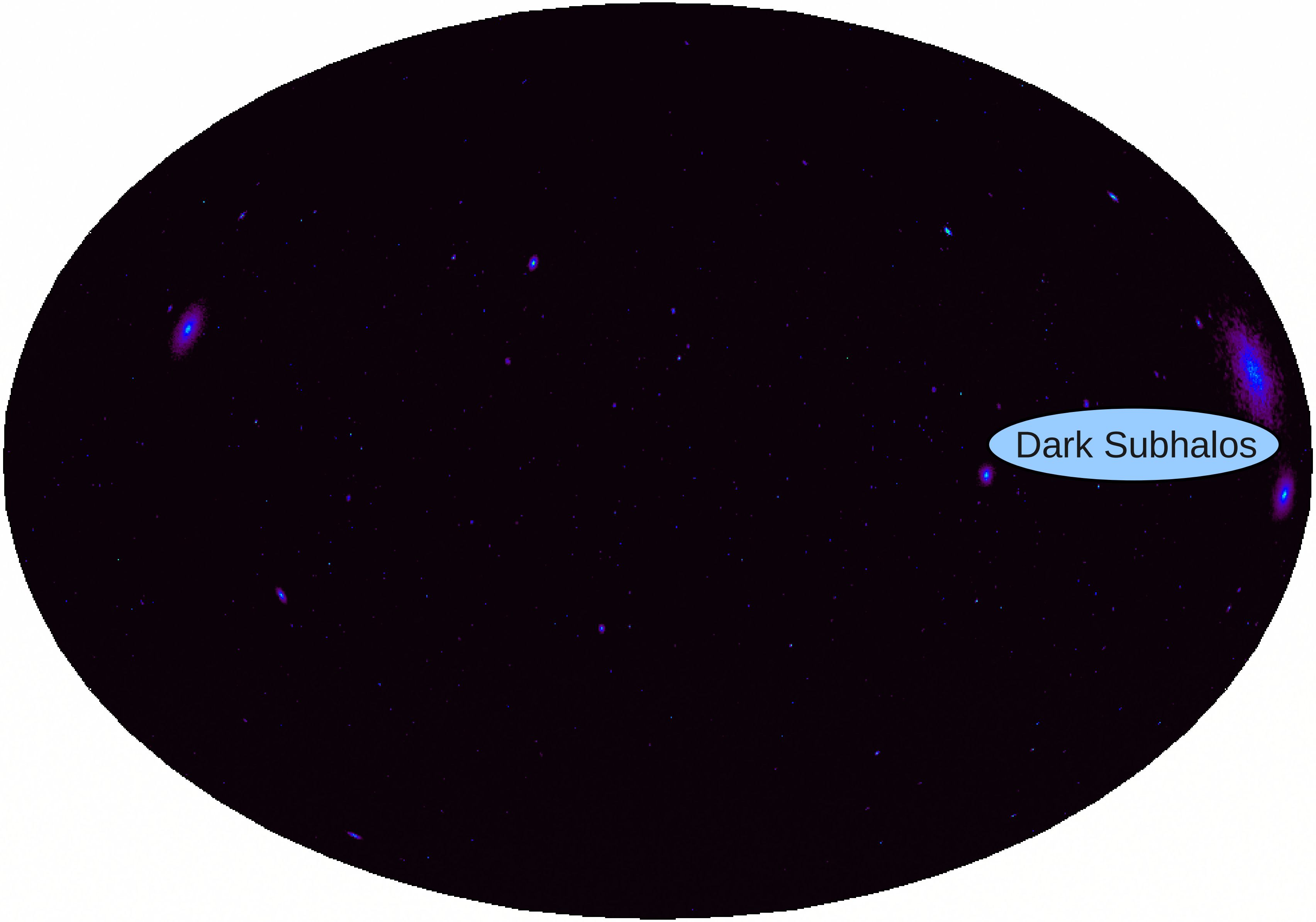
Substructure Relevance for Indirect Detection



M.L. Garde (Fermi Symposium 2011)

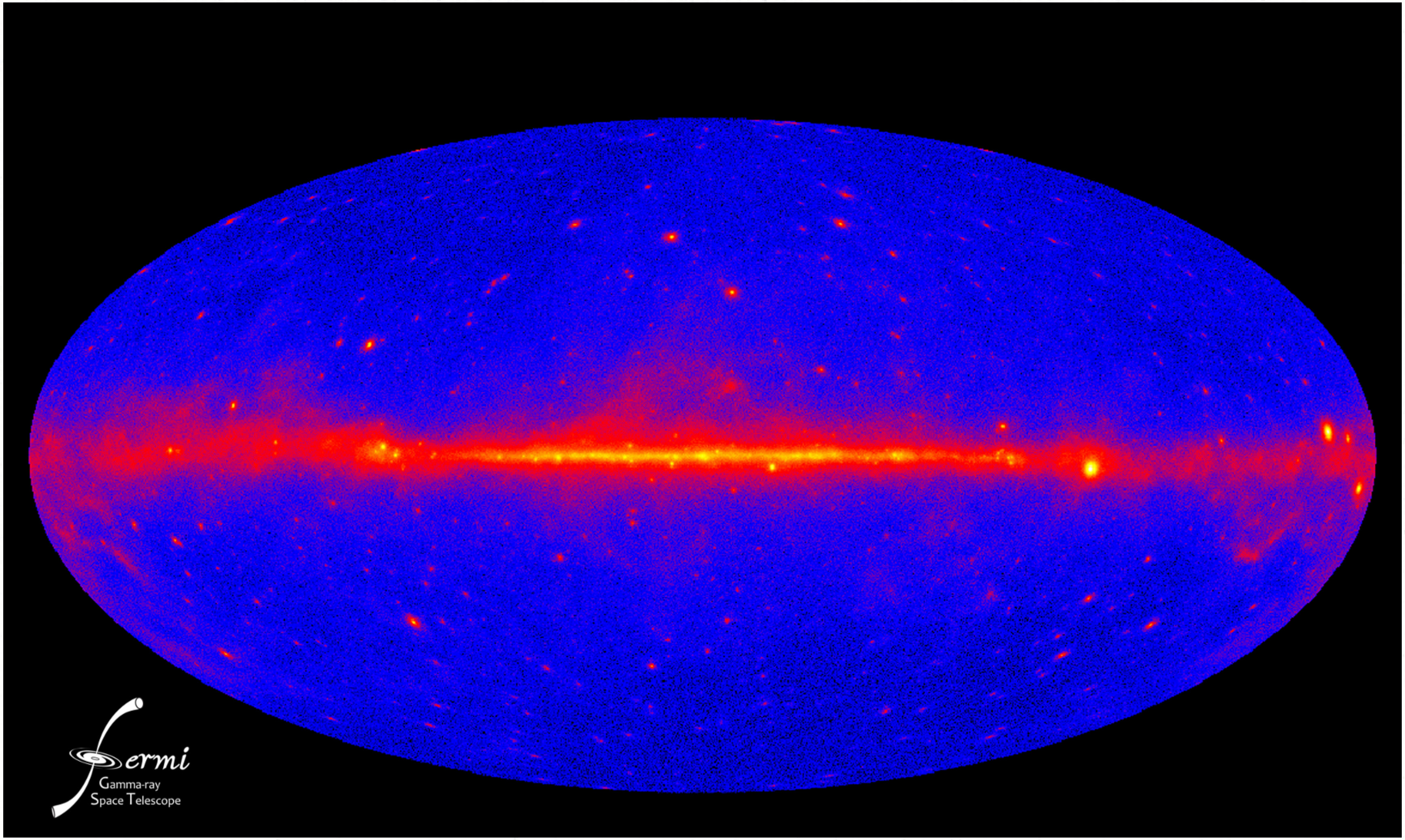
Abdo et al. (2010)

Substructure Relevance for Indirect Detection



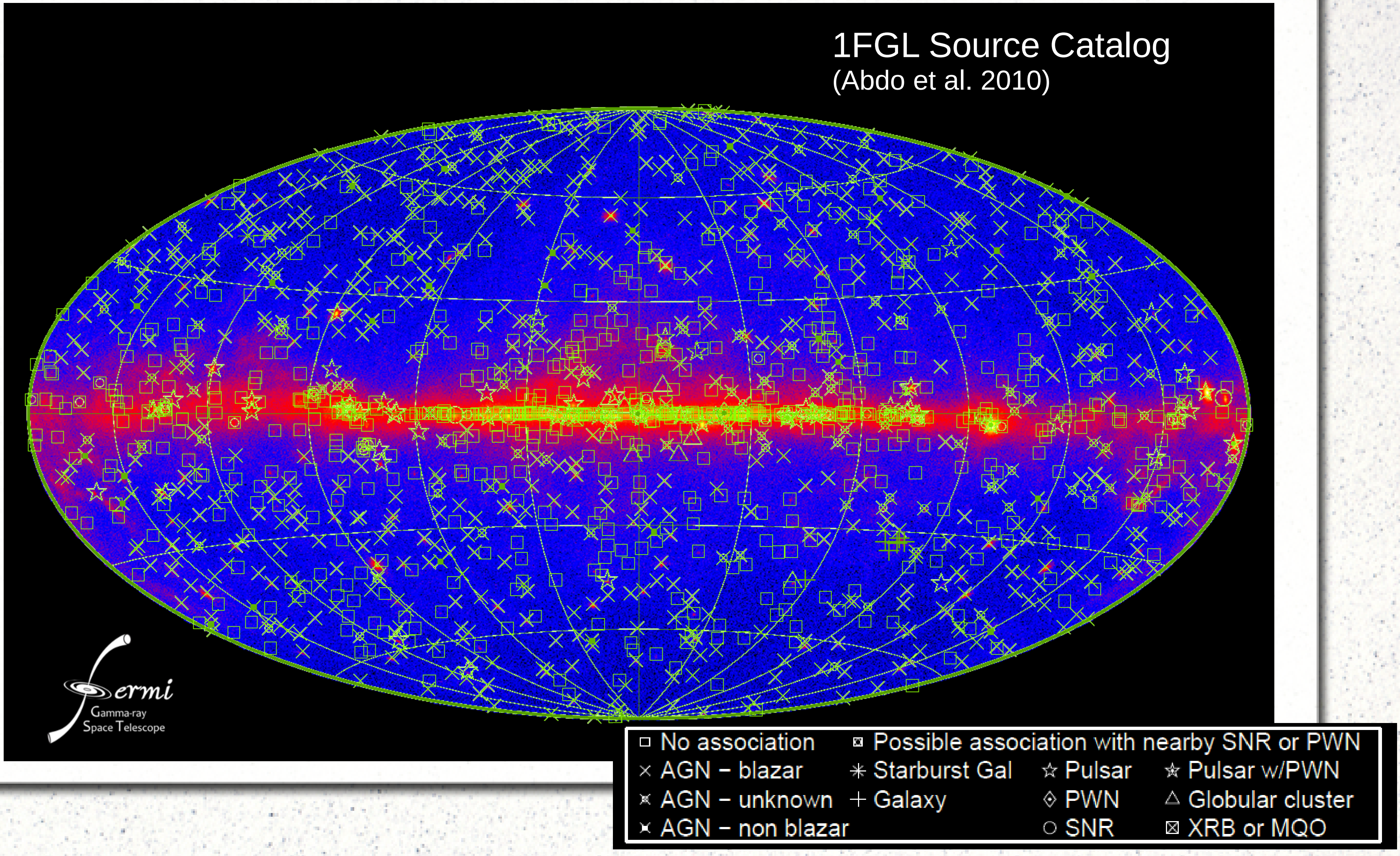
Indirect Detection of Subhalos

The Fermi Gamma-ray Space Telescope was launched on June 11th 2008 and has been observing the sky for more than 2 years.

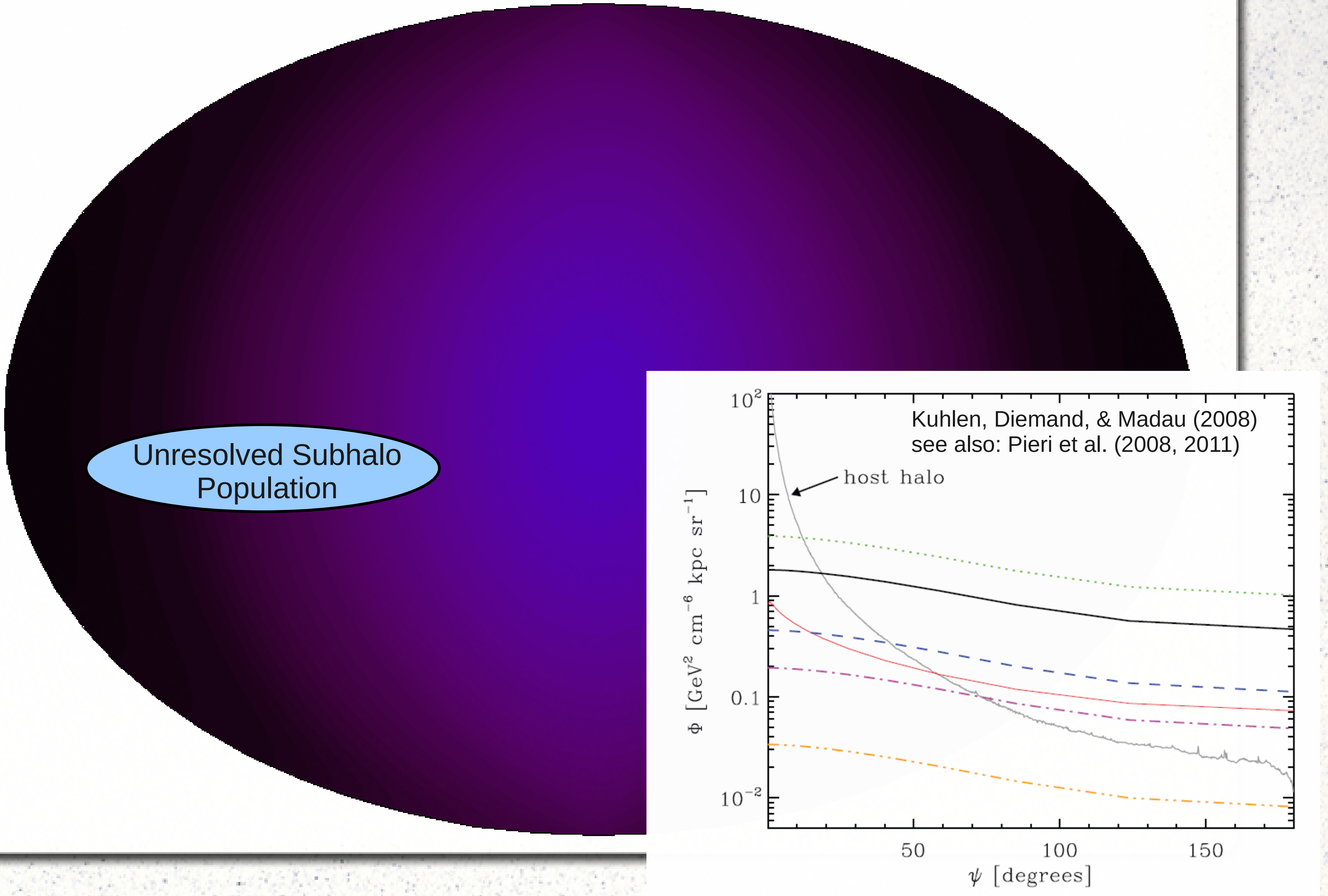


Indirect Detection of Subhalos

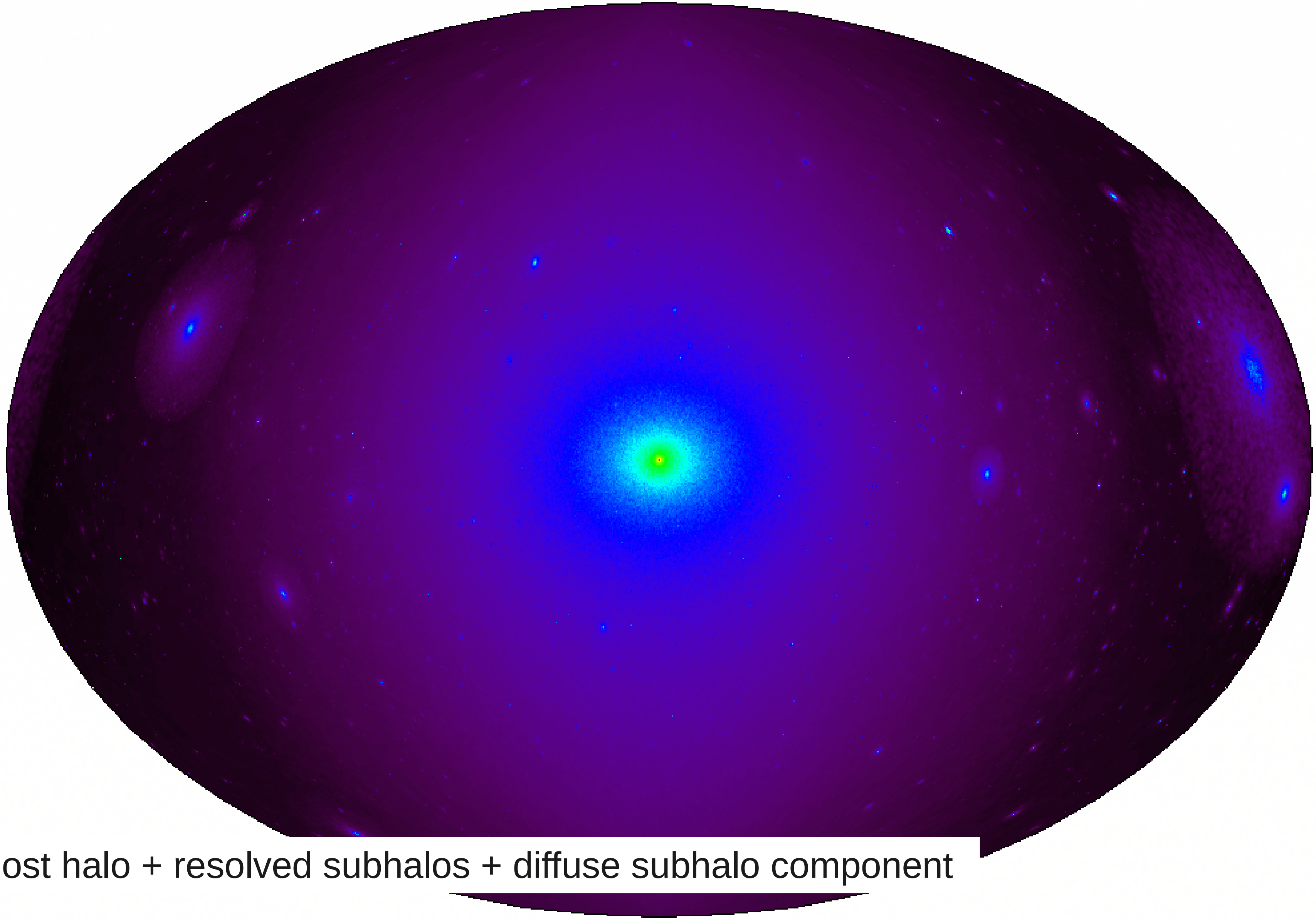
So far, now dark matter signal has been detected. ☹   Stay tuned...



Substructure Relevance for Indirect Detection

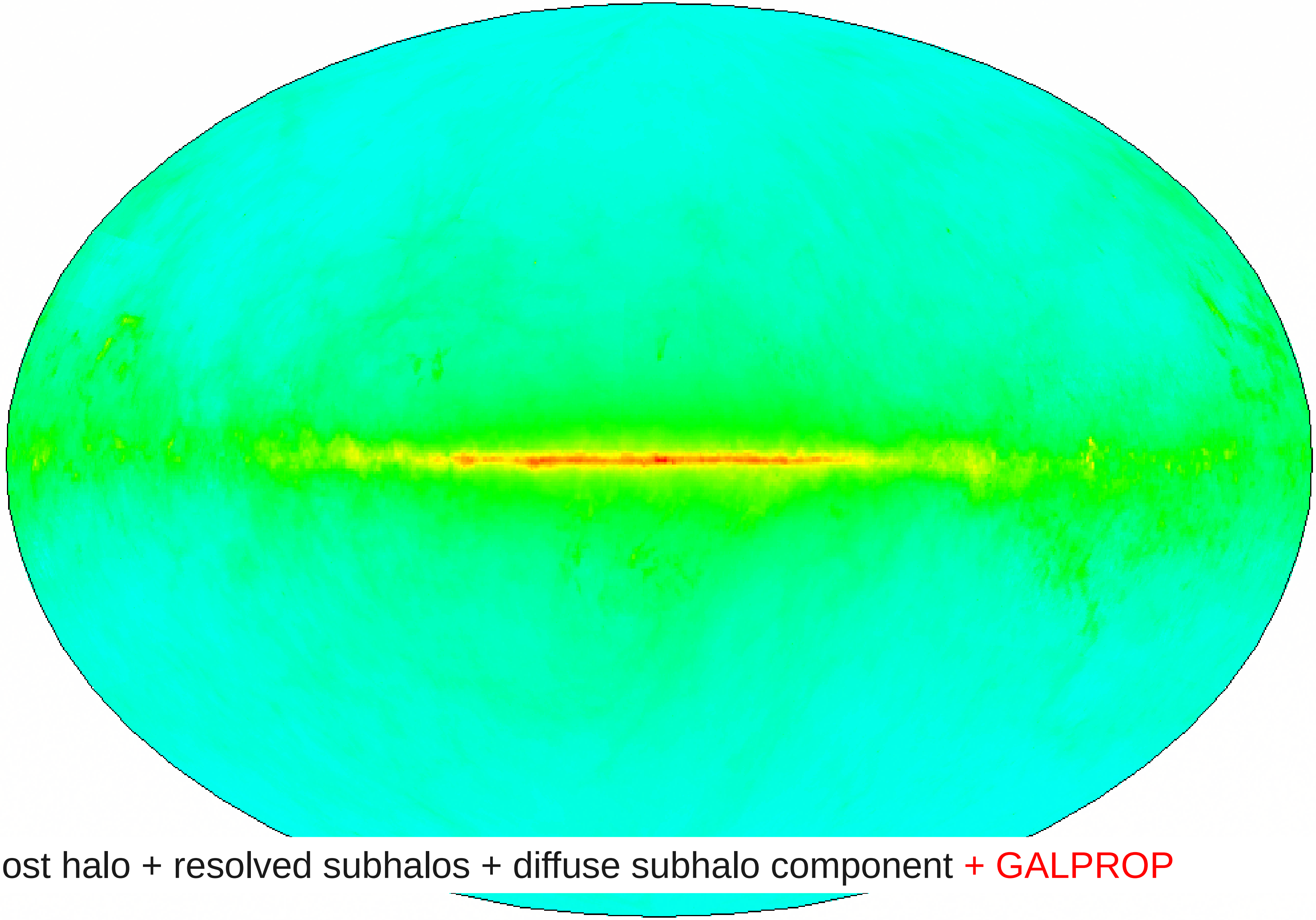


Substructure Relevance for Indirect Detection



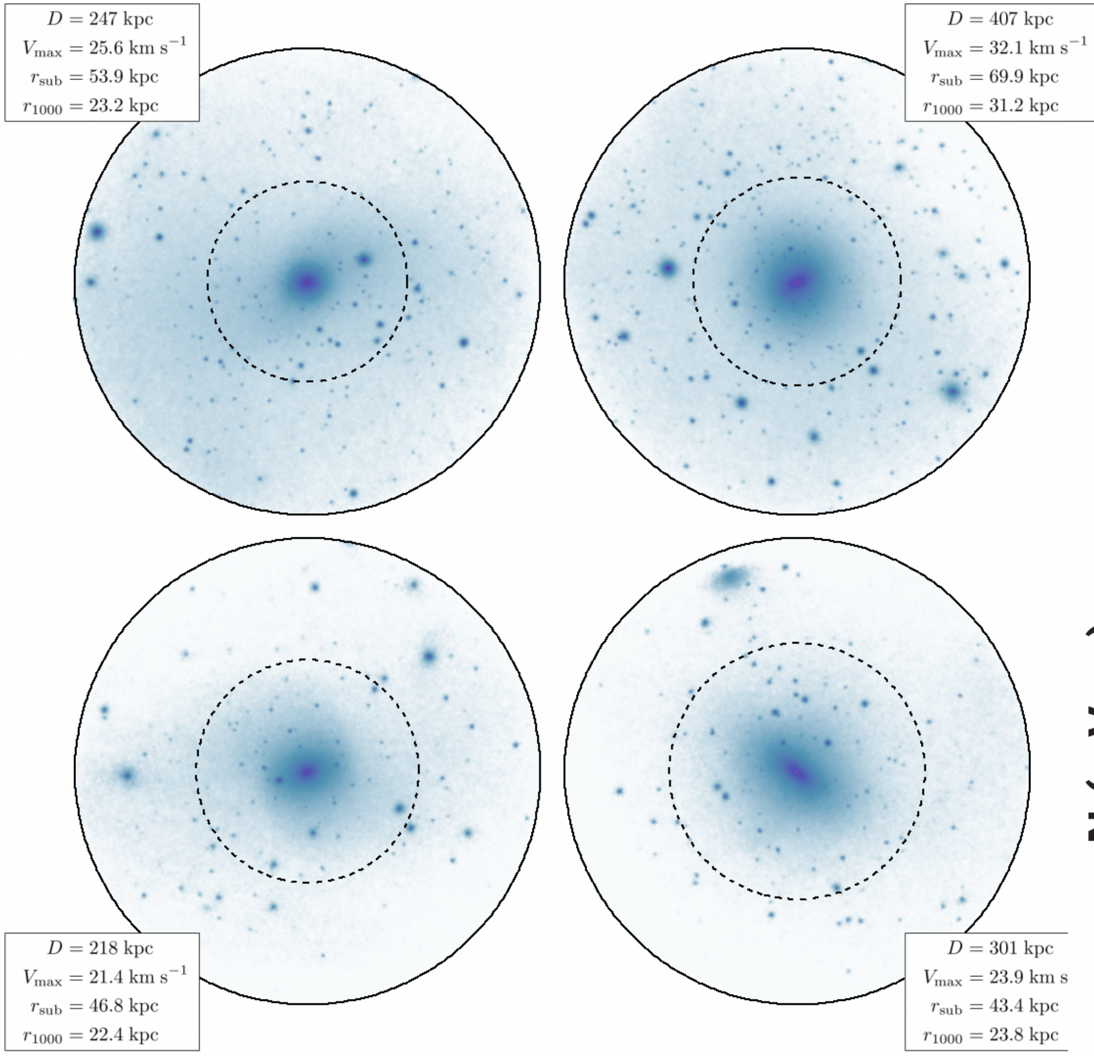
host halo + resolved subhalos + diffuse subhalo component

Substructure Relevance for Indirect Detection



host halo + resolved subhalos + diffuse subhalo component + GALPROP

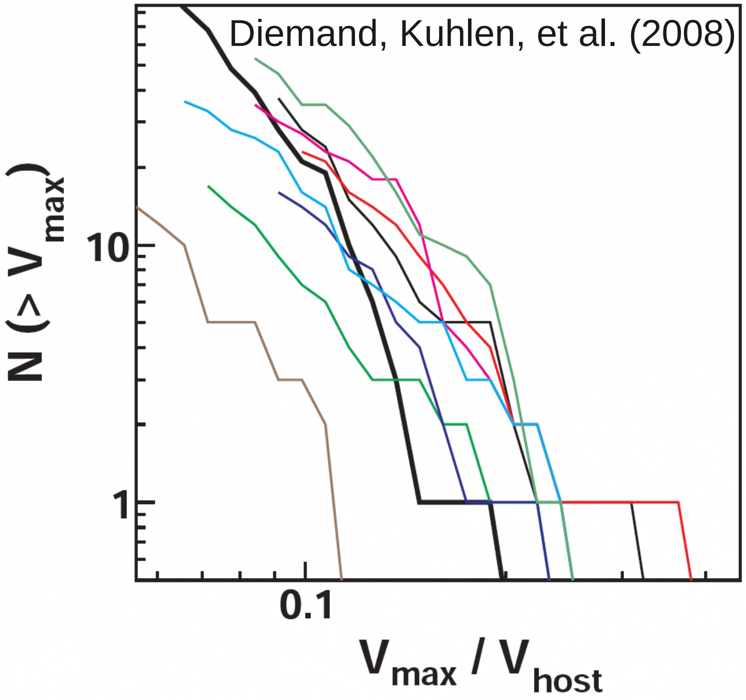
Substructure, Sub-substructure, Sub-sub-sub...



Kuhlen, Diemand, & Madau (2008)

$$\langle \rho \rangle^2 \neq \langle \rho^2 \rangle$$

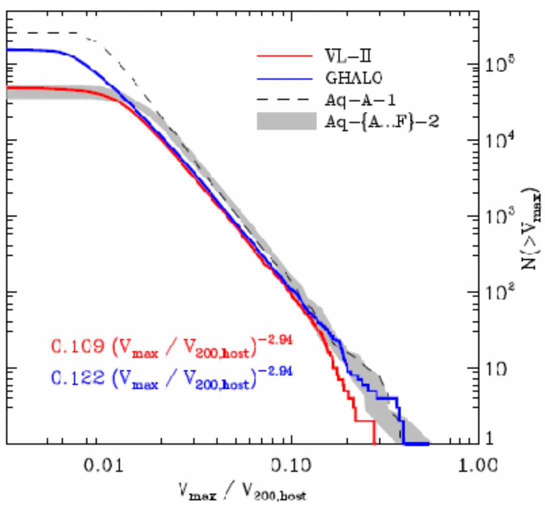
A clumpy DM distribution leads to a luminosity enhancement – the **substructure boost factor**



Substructure Boost: Subhalo Modeling Approach

Calibrate to numerical simulations.
Must extrapolate below resolution limit (“only” 12 orders of magnitude...)

Mass/V_{max} function:

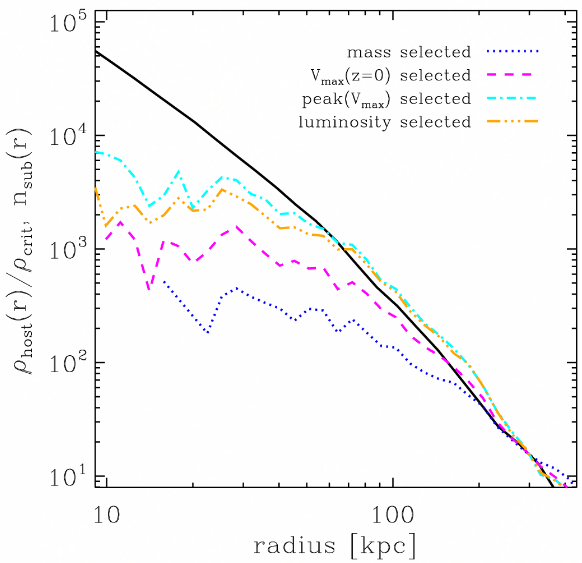


The subhalo mass function is steeply rising towards low masses.

$$\frac{dN}{dM} \sim M^{-\gamma} \quad \gamma \approx 1.9$$

$$N(>V_{\rm max}) \sim V_{\rm max}^{-\delta} \quad \delta \approx 3$$

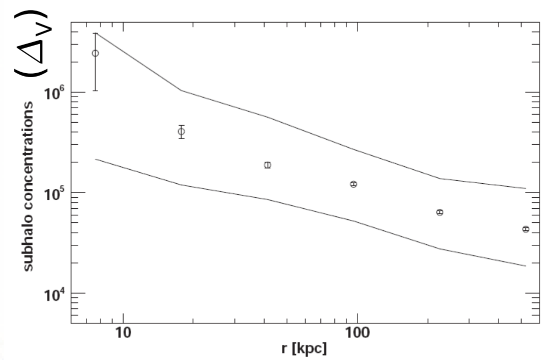
Radial Distribution:



The mass-selected distribution is “anti-biased” but a luminosity-selected sample less so.

Concentration:

$$L_{\rm ann} \sim \frac{M^2}{R^3}\frac{c^3}{f(c)^2}$$
$$\sim V_{\rm max}^3 \sqrt{\Delta_V}$$

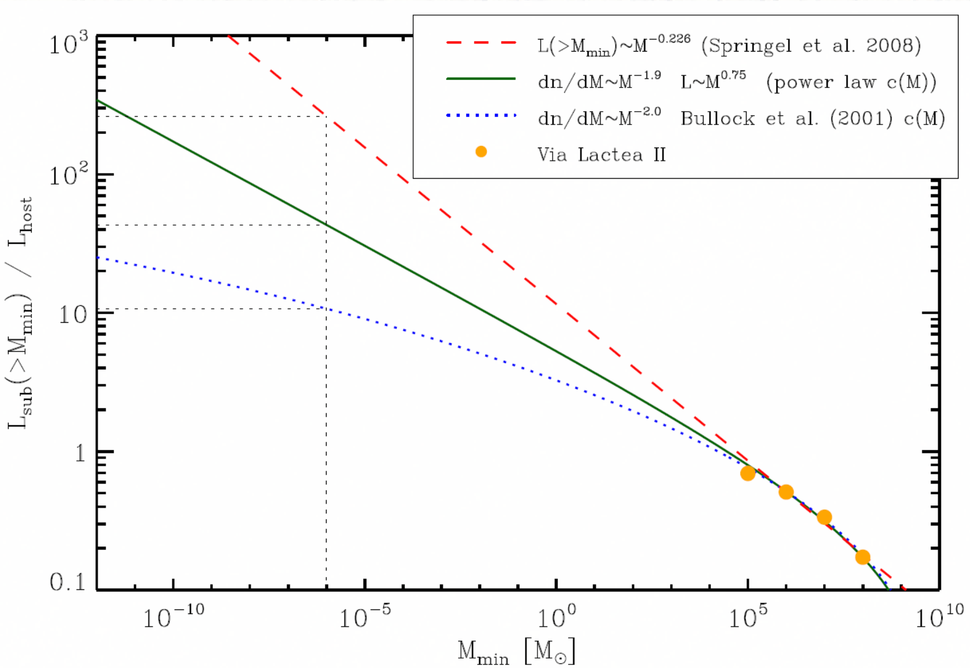


$$\Delta_V = \langle \rho(<\mathrm{R}_{\mathrm{V}_{\max}}) \rangle / \rho_{\rm crit}$$

is a measure of subhalo concentration. It rises towards the center.

Substructure Boost: Subhalo Modeling Approach

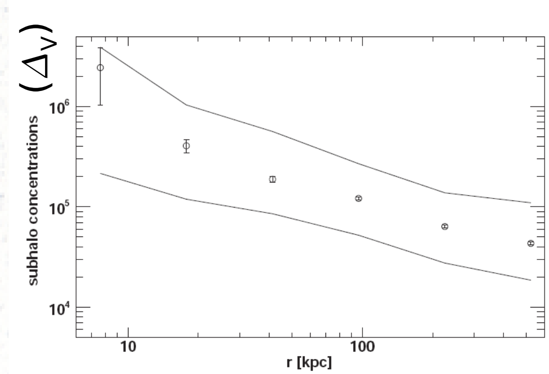
Calibrate to numerical simulations.
Must extrapolate below resolution limit ("only" 12 orders of magnitude...)



Concentration:

$$L_{\rm ann} \sim \frac{M^2}{R^3}\,\frac{c^3}{f(c)^2}$$

$$\sim V_{\rm max}^3 \sqrt{\Delta_V}$$



Depends **critically** on what one assumes for the concentration-mass relation for subhalos below the simulations' resolution limit!

$$\Delta_V = \langle \rho(<{\rm R}_{\rm V_{max}}) \rangle / \rho_{\rm crit}$$

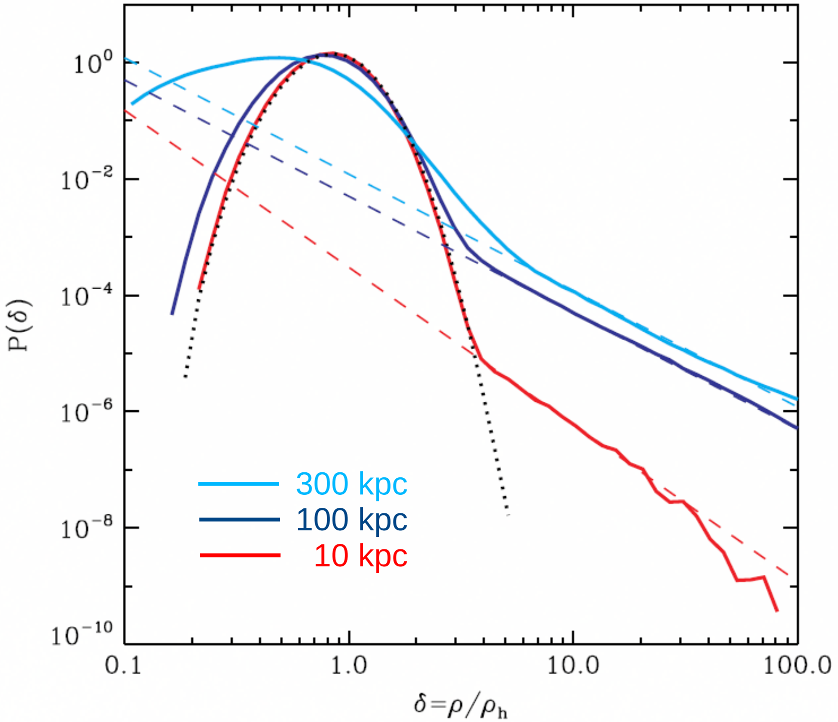
is a measure of subhalo concentration. It rises towards the center.

See also: Martinez, Bullock, Kaplinghat, Strigari, & Trotta (2010)

Substructure Boost: Density Distribution Approach

Measure the PDF of ρ/ρ_{host} in the simulation.

It's fit well by a **log-normal** plus a **powerlaw** tail due to substructure.



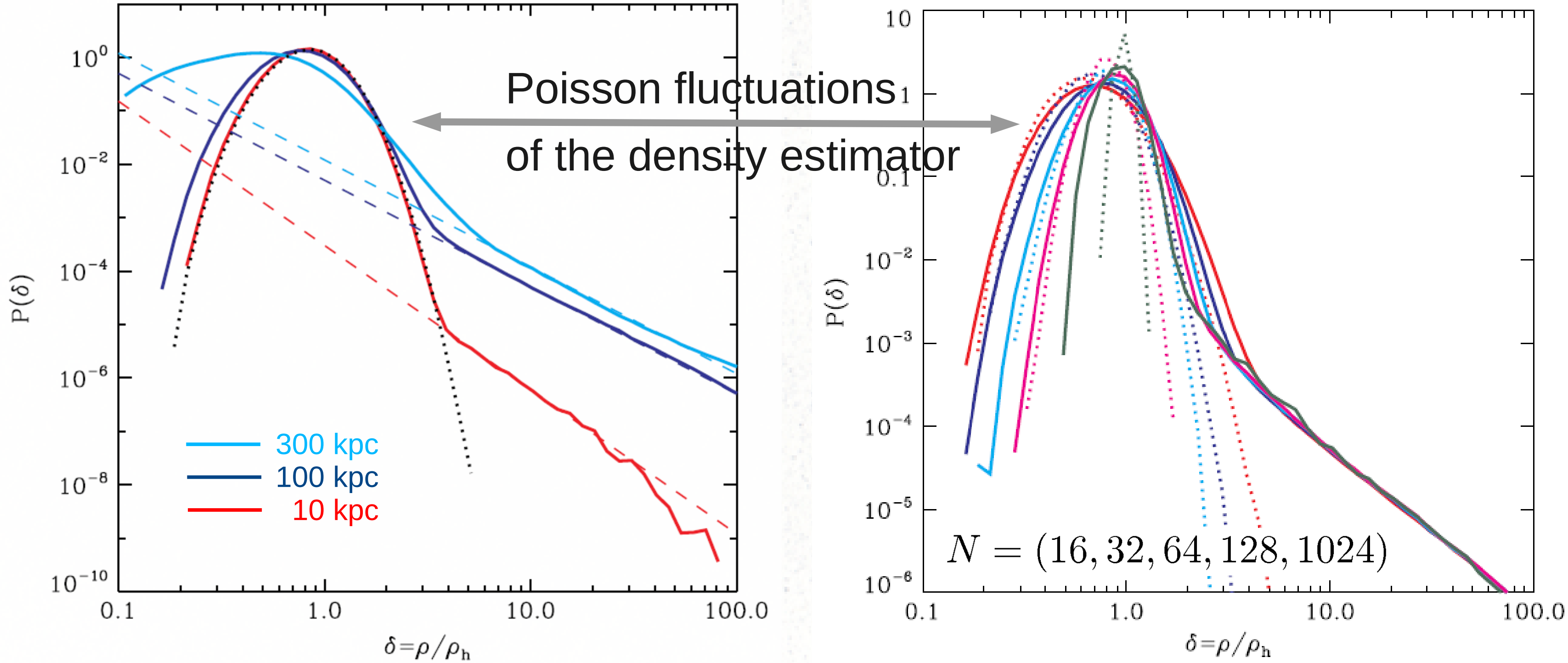
$$P(\rho;r) = \frac{f_s}{\sqrt{2\pi\Delta^2}}\frac{1}{\rho}\exp\left\{-\frac{1}{2\Delta^2}\left[\ln\left(\frac{\rho}{\rho_h}e^{\Delta^2/2}\right)\right]^2\right\} + (1-f_s)\frac{1+\alpha(r)}{\rho_h}\Theta(\rho-\rho_h)\left(\frac{\rho}{\rho_h}\right)^{-(2+\alpha)}$$

Kamionkowski, Koushiappas & Kuhlen (2010)

Substructure Boost: Density Distribution Approach

Measure the PDF of $\rho/\rho_{\mathrm{host}}$ in the simulation.

It's fit well by a **log-normal** plus a **powerlaw** tail due to substructure.



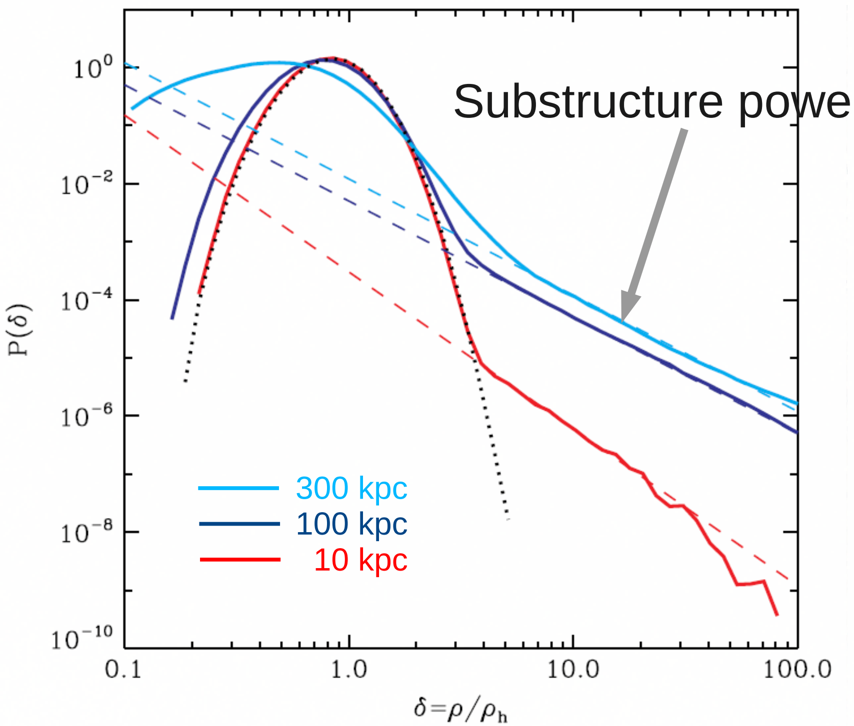
$$P(\rho; r) = \frac{f_s}{\sqrt{2\pi\Delta^2}} \frac{1}{\rho} \exp\left\{-\frac{1}{2\Delta^2}\left[\ln\left(\frac{\rho}{\rho_h} e^{\Delta^2/2}\right)\right]^2\right\} + (1 - f_s)\frac{1 + \alpha(r)}{\rho_h}\Theta(\rho - \rho_h)\left(\frac{\rho}{\rho_h}\right)^{-(2+\alpha)}$$

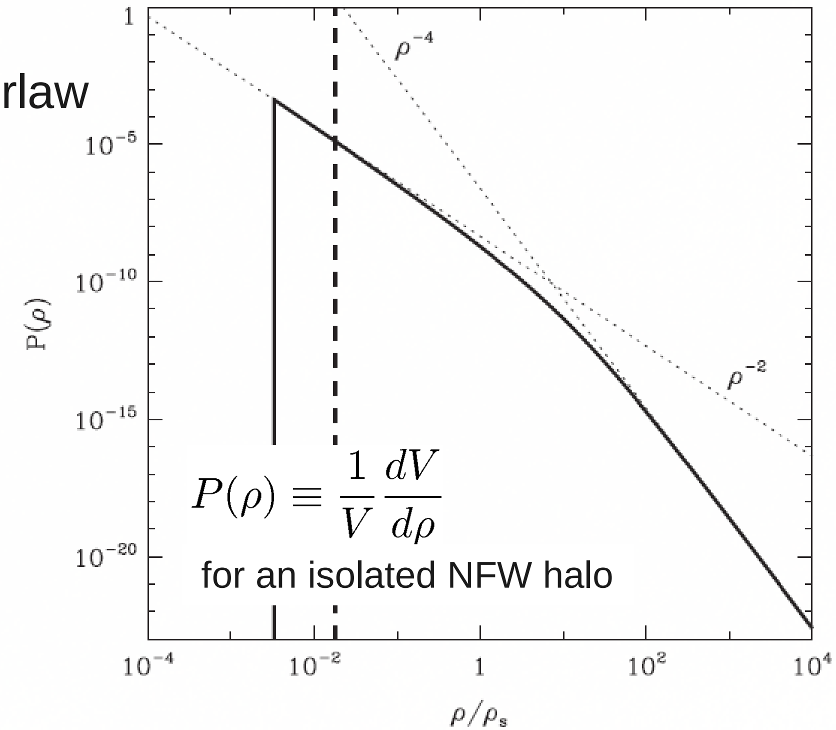
Kamionkowski, Koushiappas & Kuhlen (2010)

Substructure Boost: Density Distribution Approach

Measure the PDF of $\rho/\rho_{\rm host}$ in the simulation.

It's fit well by a **log-normal** plus a **powerlaw** tail due to substructure.





$$P(\rho; r) = \frac{f_s}{\sqrt{2\pi\Delta^2}}\frac{1}{\rho}\exp\left\{-\frac{1}{2\Delta^2}\left[\ln\left(\frac{\rho}{\rho_h}e^{\Delta^2/2}\right)\right]^2\right\} + (1-f_s)\frac{1+\alpha(r)}{\rho_h}\Theta(\rho-\rho_h)\left(\frac{\rho}{\rho_h}\right)^{-(2+\alpha)}$$

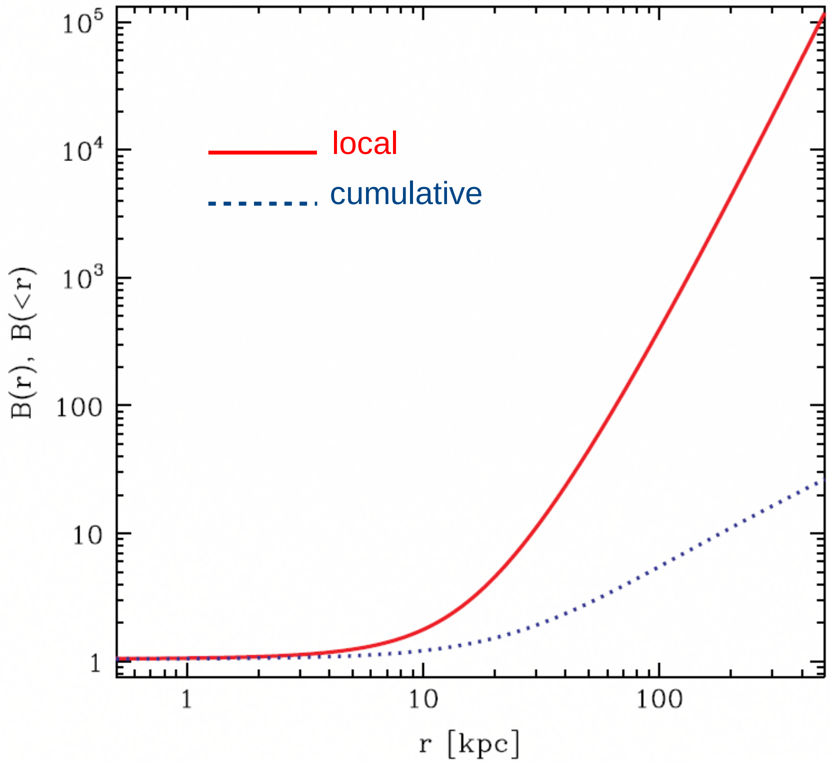
Kamionkowski, Koushiappas & Kuhlen (2010)

Substructure Boost: Density Distribution Approach

Use this distribution to calculate a boost factor as a function of radius.

$$B(r) = \frac{\int \rho^2 dV}{\int [\bar{\rho}(r)]^2 dV} = \int_0^{\rho_{\max}} P(\rho, r) \frac{\rho^2}{[\bar{\rho}(r)]^2} d\rho,$$

$$= f_s e^{\Delta^2} + (1 - f_s) \frac{1+\alpha}{1-\alpha} \left[\left(\frac{\rho_{\max}}{\rho_h} \right)^{1-\alpha} - 1 \right].$$



Depends on ρ_{max}, which is set by the halo collapse epoch:

$$\rho_{\max} = 80\,\mathrm{GeV\,cm^{-3}} \left(\frac{z_c}{40}\right)^3 \left(\frac{c}{3.5}\right) \frac{f(3.5)}{f(c)}$$

[Here c is the **natal** concentration!]

The biggest uncertainty is in f_s and its GC radius dependence.

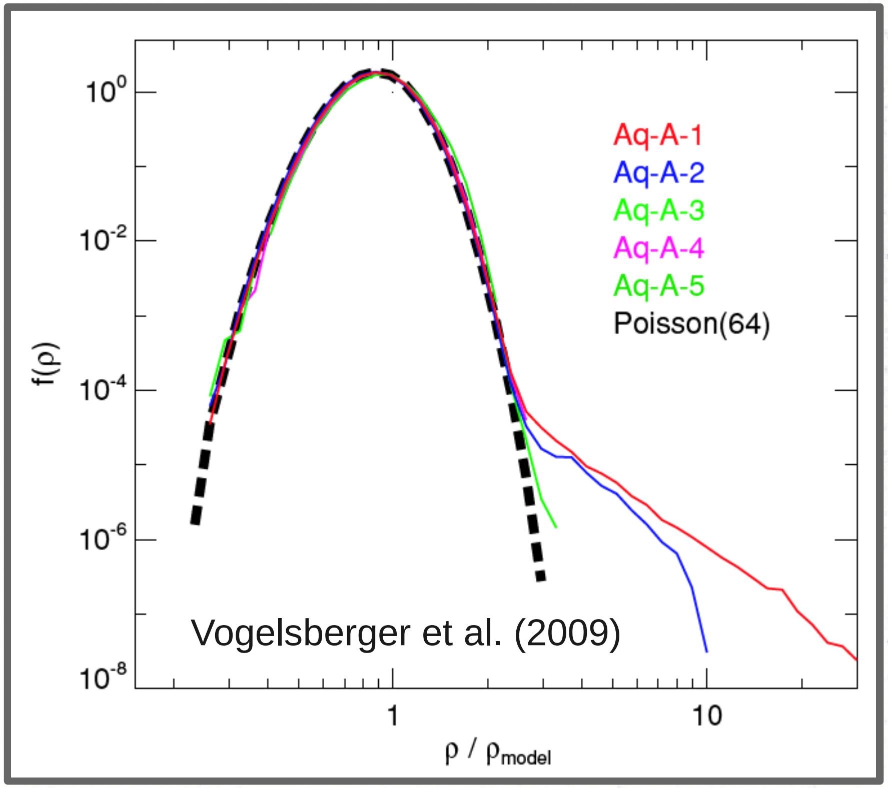
Kamionkowski, Koushiappas & Kuhlen (2010)

Substructure Boost: Density Distribution Approach

Use this distribution to calculate a boost factor as a function of radius.

$$B(r) = \frac{\int \rho^2 dV}{\int [\bar{\rho}(r)]^2 dV} = \int_0^{\rho_{\max}} P(\rho, r) \frac{\rho^2}{[\bar{\rho}(r)]^2} d\rho,$$

$$= f_s e^{\Delta^2} + (1 - f_s) \frac{1 + \alpha}{1 - \alpha} \left[\left(\frac{\rho_{\max}}{\rho_h} \right)^{1-\alpha} - 1 \right].$$



Depends on $\rho_{\max}$, which is set by the halo collapse epoch:

$$\rho_{\max} = 80\,\mathrm{GeV\,cm^{-3}} \left(\frac{z_c}{40}\right)^3 \left(\frac{c}{3.5}\right) \frac{f(3.5)}{f(c)}$$

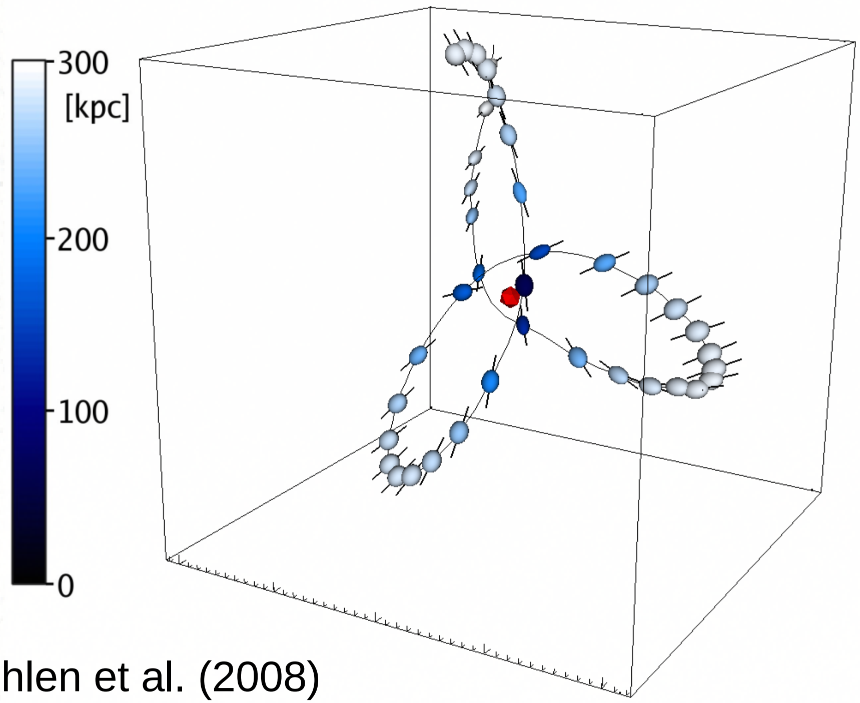
[Here c is the **natal** concentration!]

The biggest uncertainty is in f_s and its GC radius dependence.

Kamionkowski, Koushiappas & Kuhlen (2010)

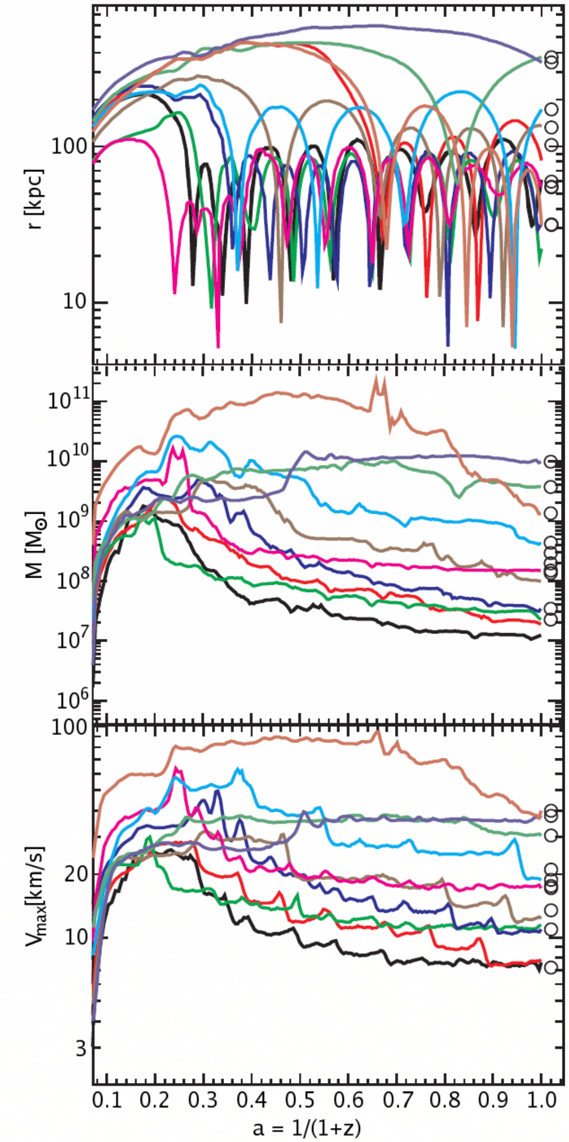
Tidal Interactions with the Host Halo

- Subhalos orbit through host halo and are subject to tidal interactions.
- Strongest during peri-center passage.
- Tidal mass loss from outside in.
- Diverse amount of tidal mass loss.



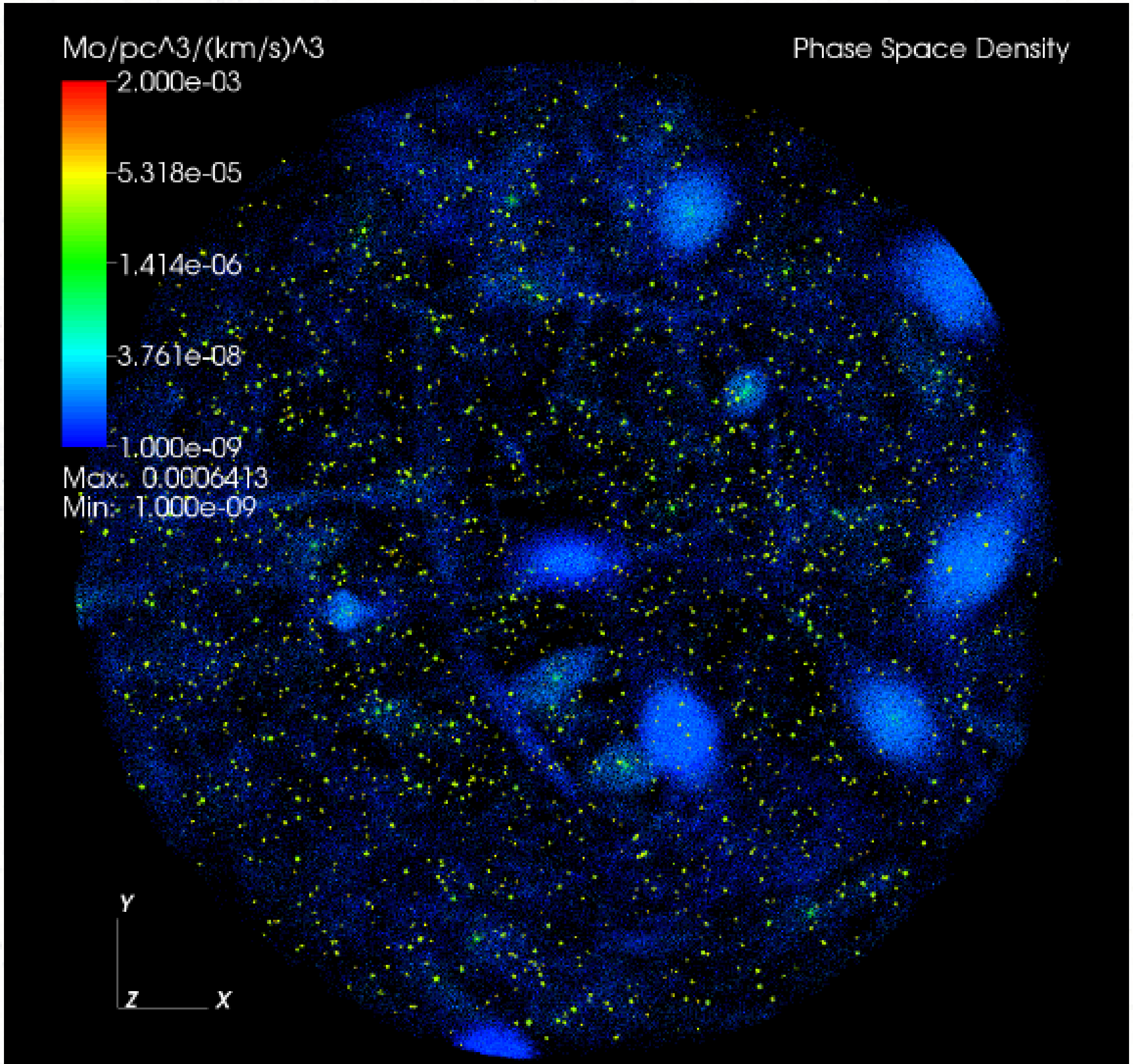
Kuhlen et al. (2008)

Diemand, Kuhlen, et al. (2008)



Velocity Space Substructure

When viewed in **phase-space-density**, many additional unbound substructures become apparent: dark matter tidal streams from disrupted subhalos.



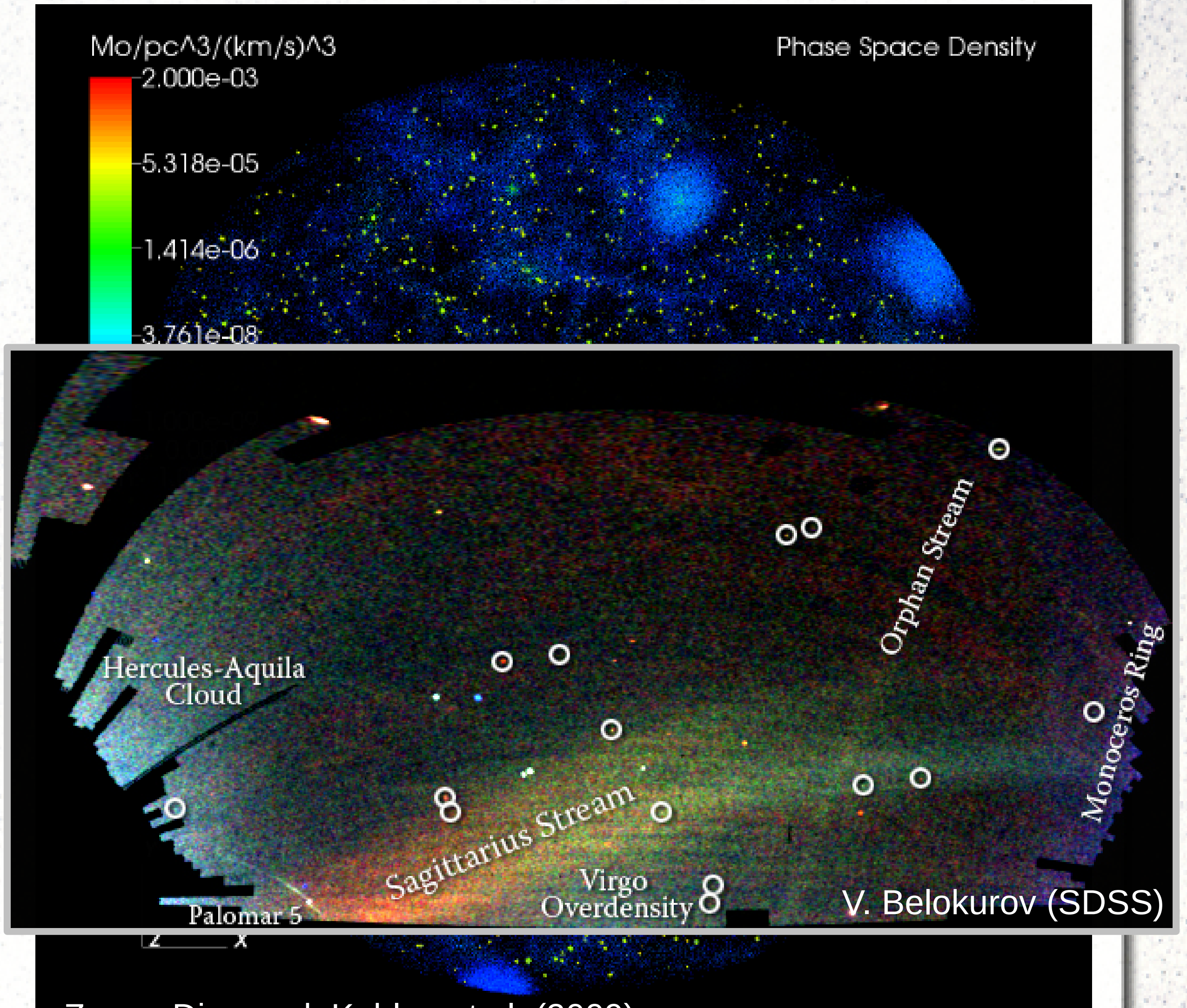
Zemp, Diemand, Kuhlen et al. (2009)

Velocity Space Substructure

When viewed in **phase-space-density**, many additional unbound substructures become apparent: dark matter tidal streams from disrupted subhalos.

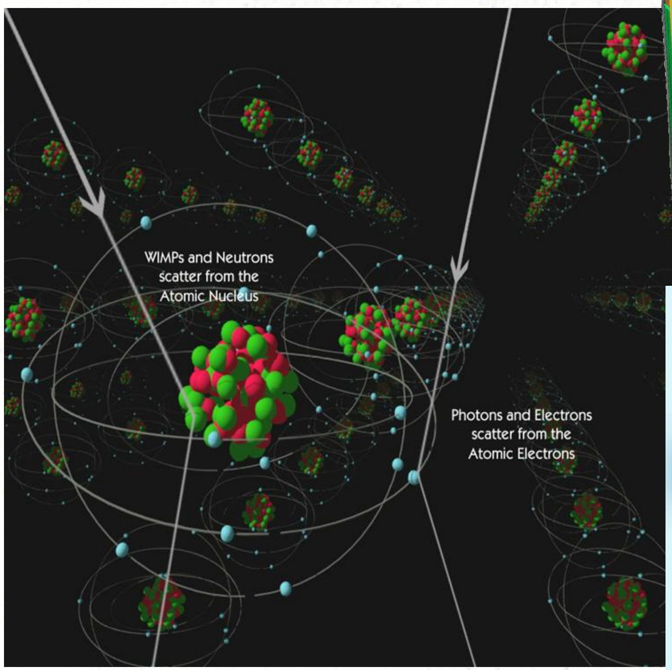
Direct counterparts to the stellar streams from disrupted satellites (e.g. SDSS Field of Streams).

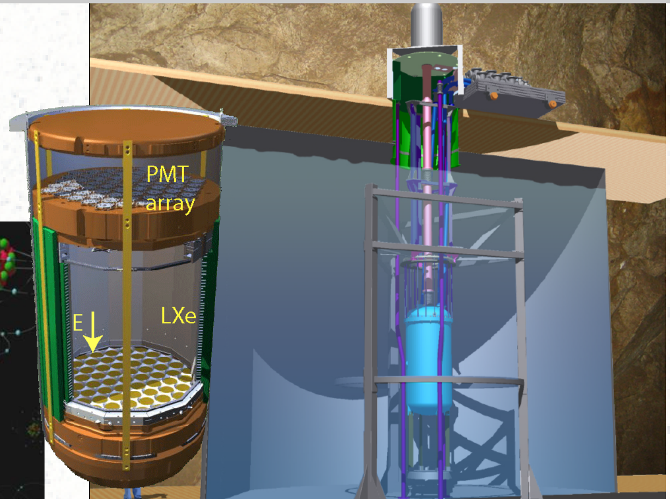
In the future will there be a Missing Streams Problem?

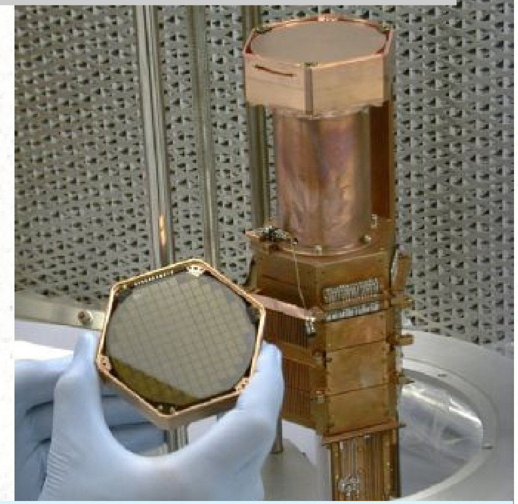


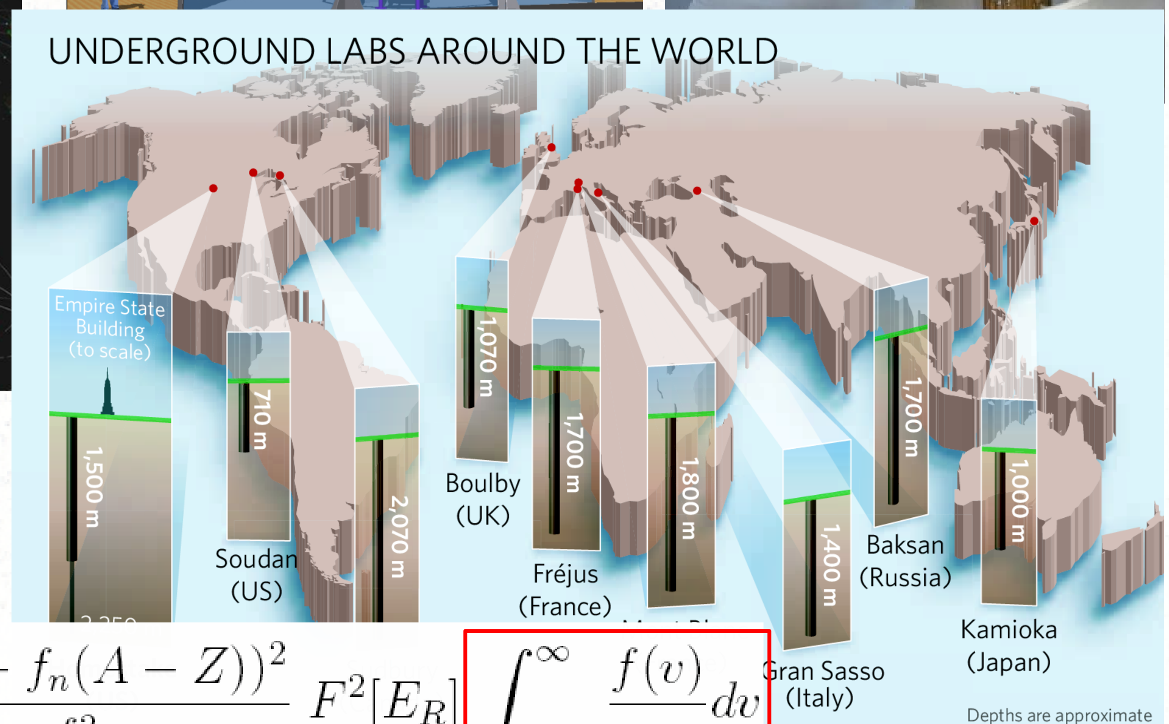
V. Belokurov (SDSS)
Zemp, Diemand, Kuhlen et al. (2009)

Velocity Space Substructure and Direct Detection



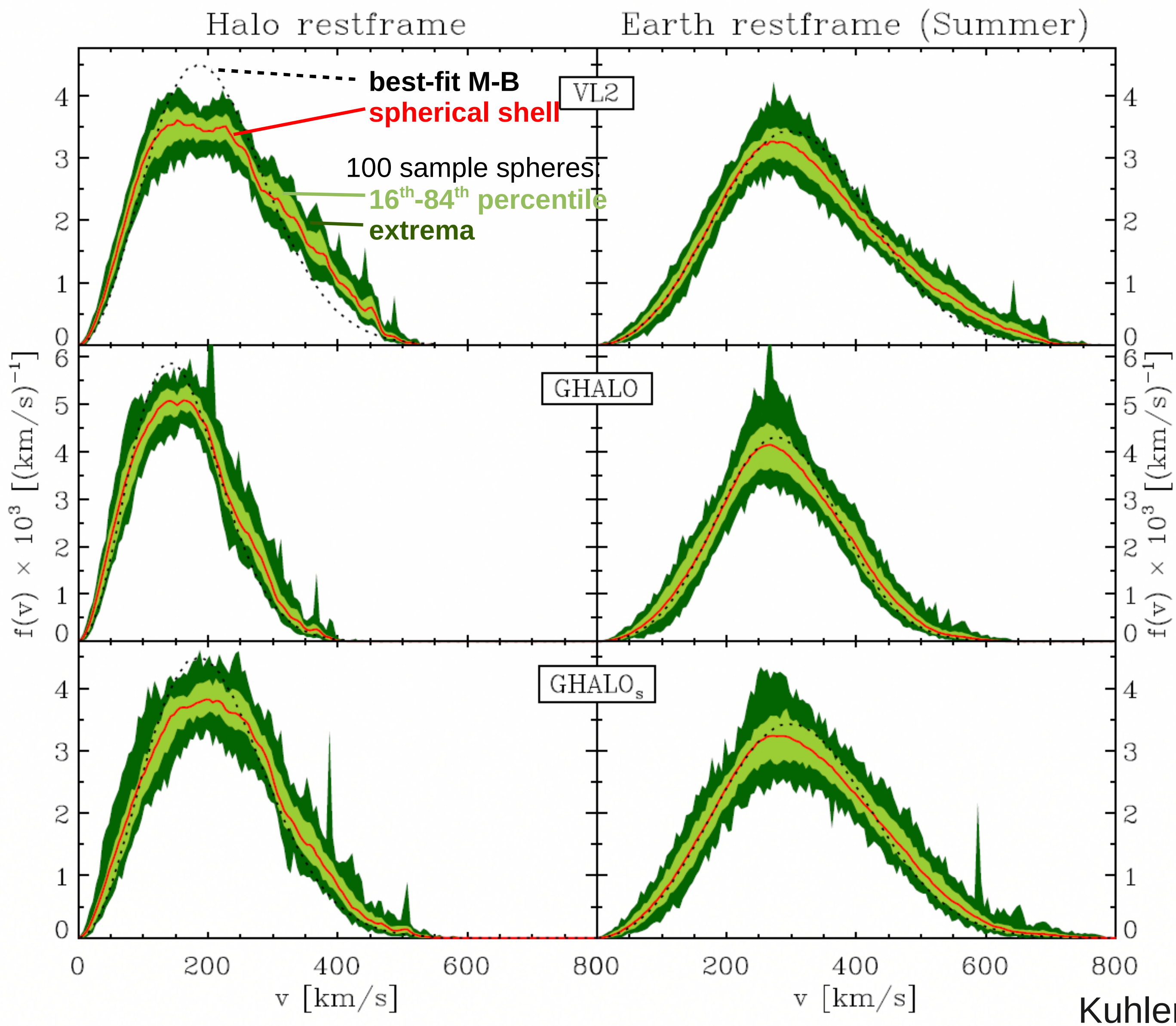






$$\frac{dR}{dE_R} = N_T M_N \frac{\rho_\chi \sigma_n}{2 m_\chi \mu_{ne}^2} \frac{(f_p Z + f_n (A - Z))^2}{f_n^2} F^2[E_R] \int_{\beta_{min}}^{\infty} \frac{f(v)}{v} dv$$

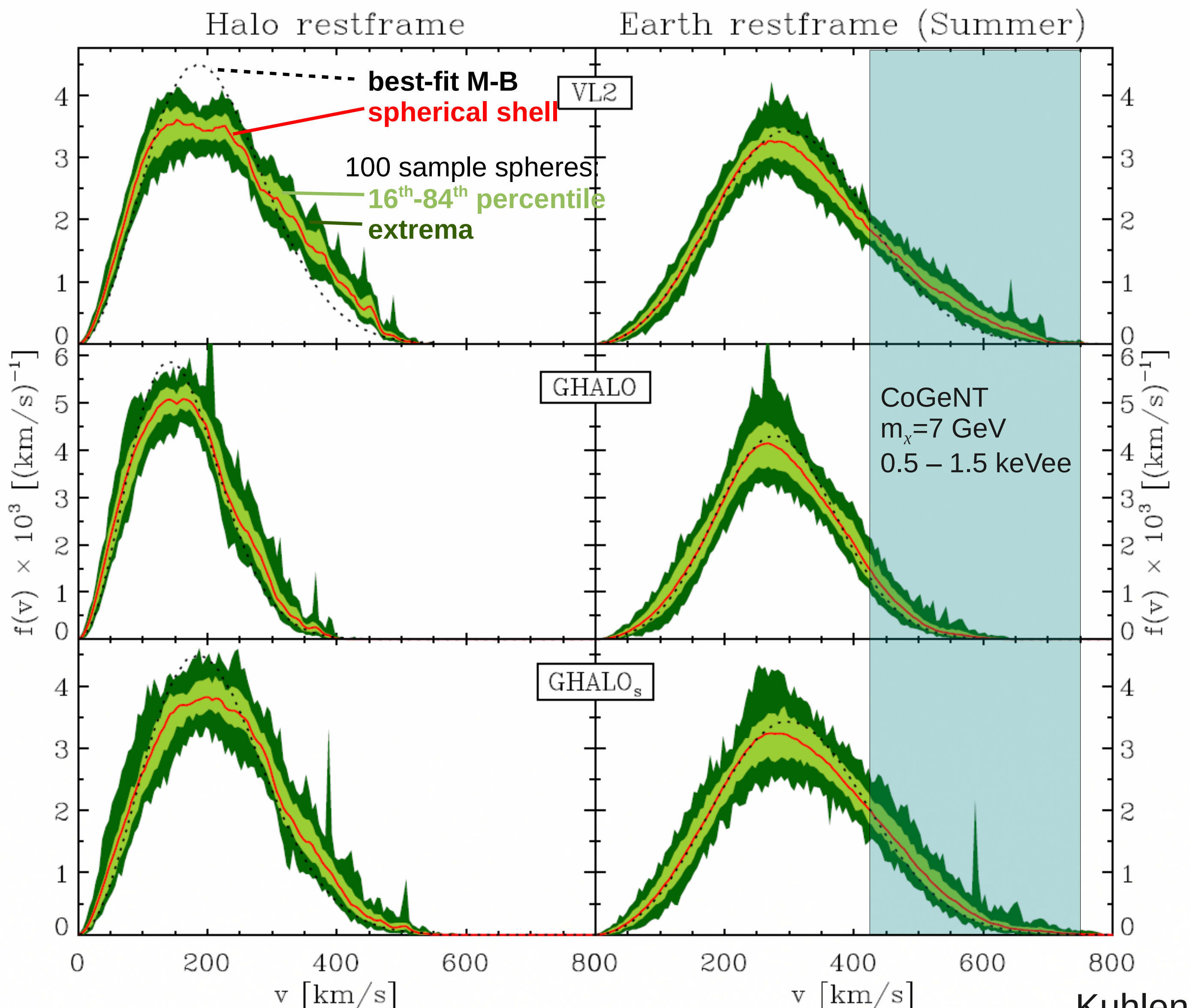
Velocity Space Substructure and Direct Detection



Kuhlen et al. (2010)

See also: Hansen et al. (2005), Vogelsberger et al. (2009)

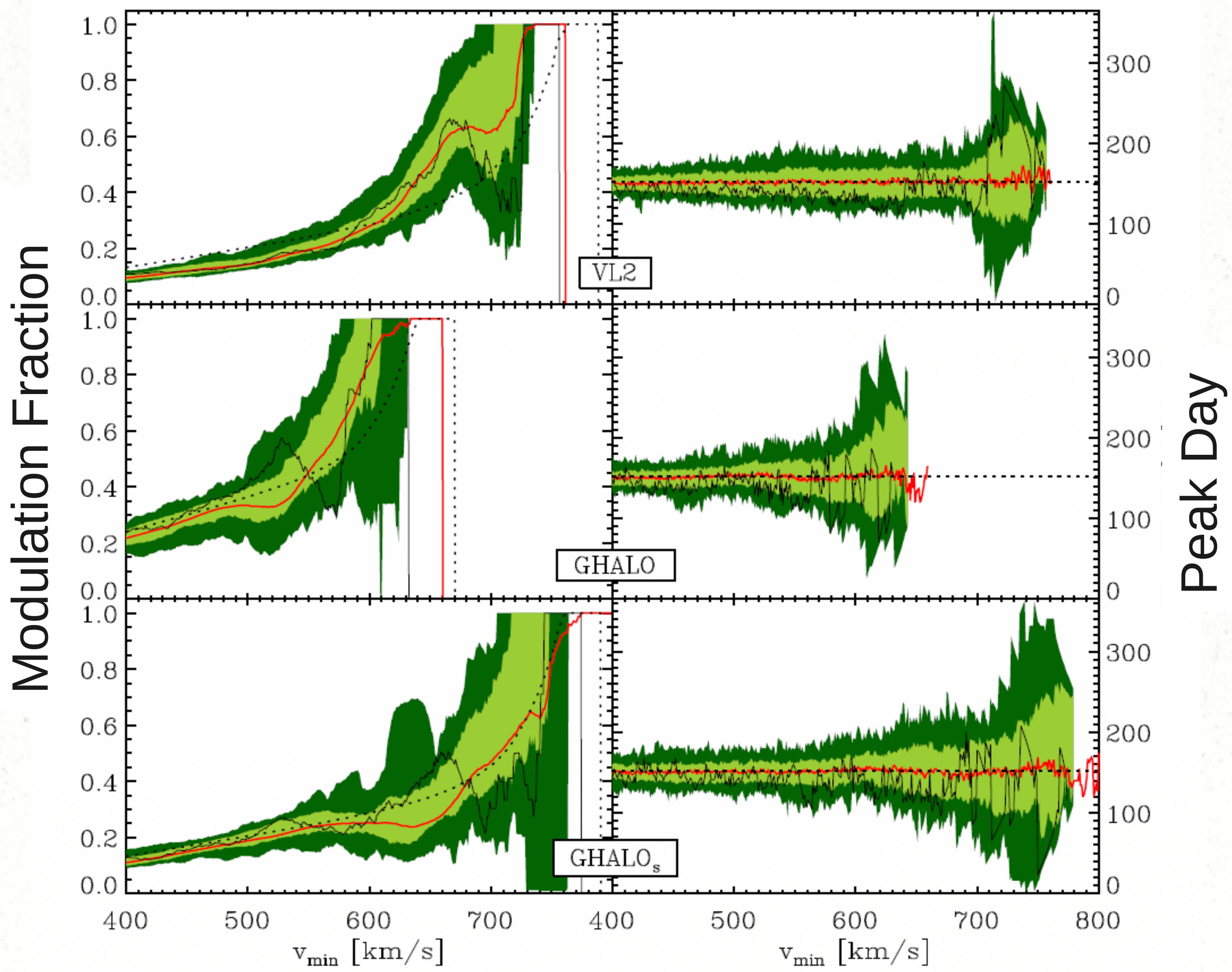
Velocity Space Substructure and Direct Detection



Kuhlen et al. (2010)

See also: Hansen et al. (2005), Vogelsberger et al. (2009)

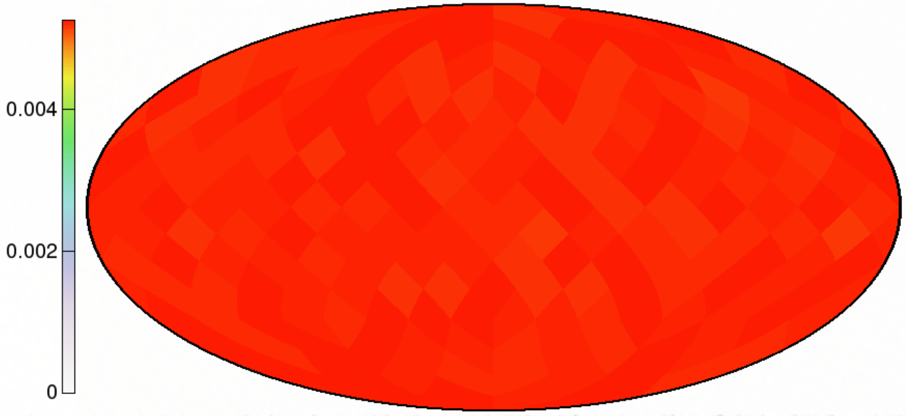
Velocity Space Substructure and Direct Detection



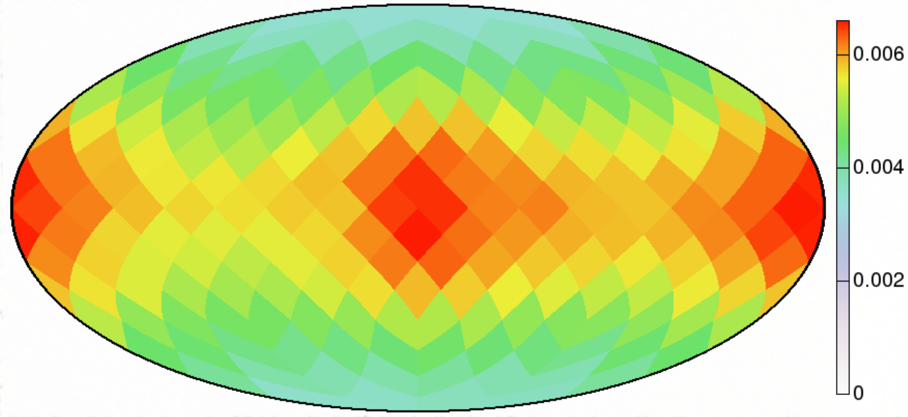
Kuhlen et al. (2010)

In Halo Restframe (v_{min} = 0 km/s)

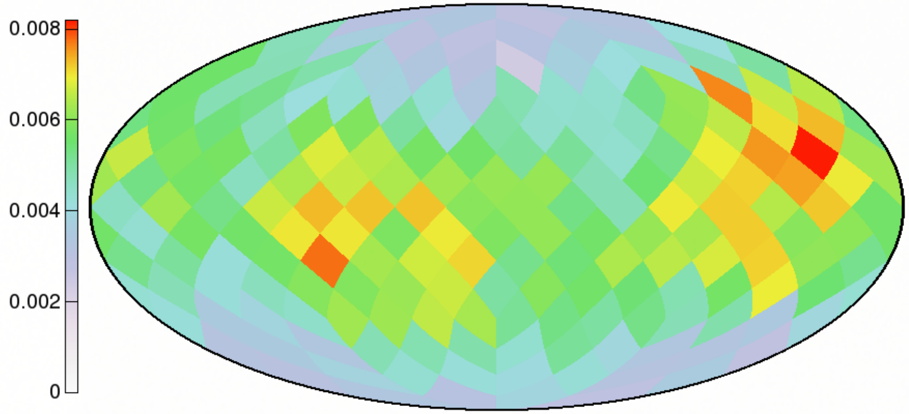
Maxwell-Boltzmann (isotropic)



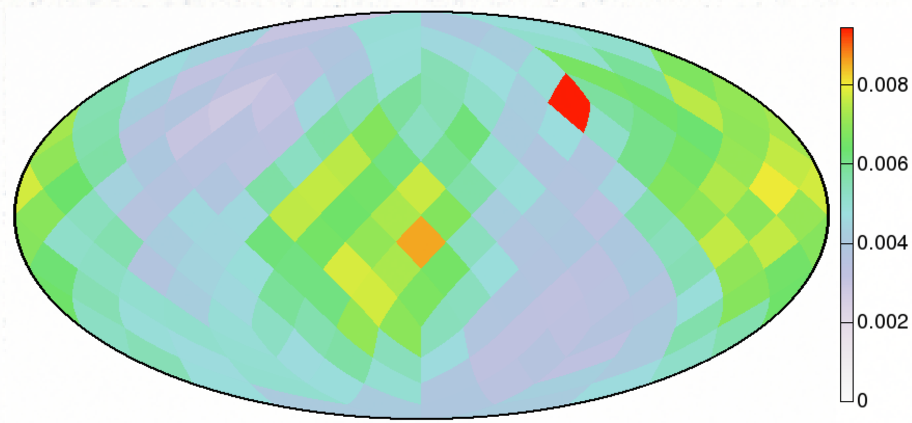
Spherical Shell (8 kpc < R < 9 kpc)



Sample Sphere #001



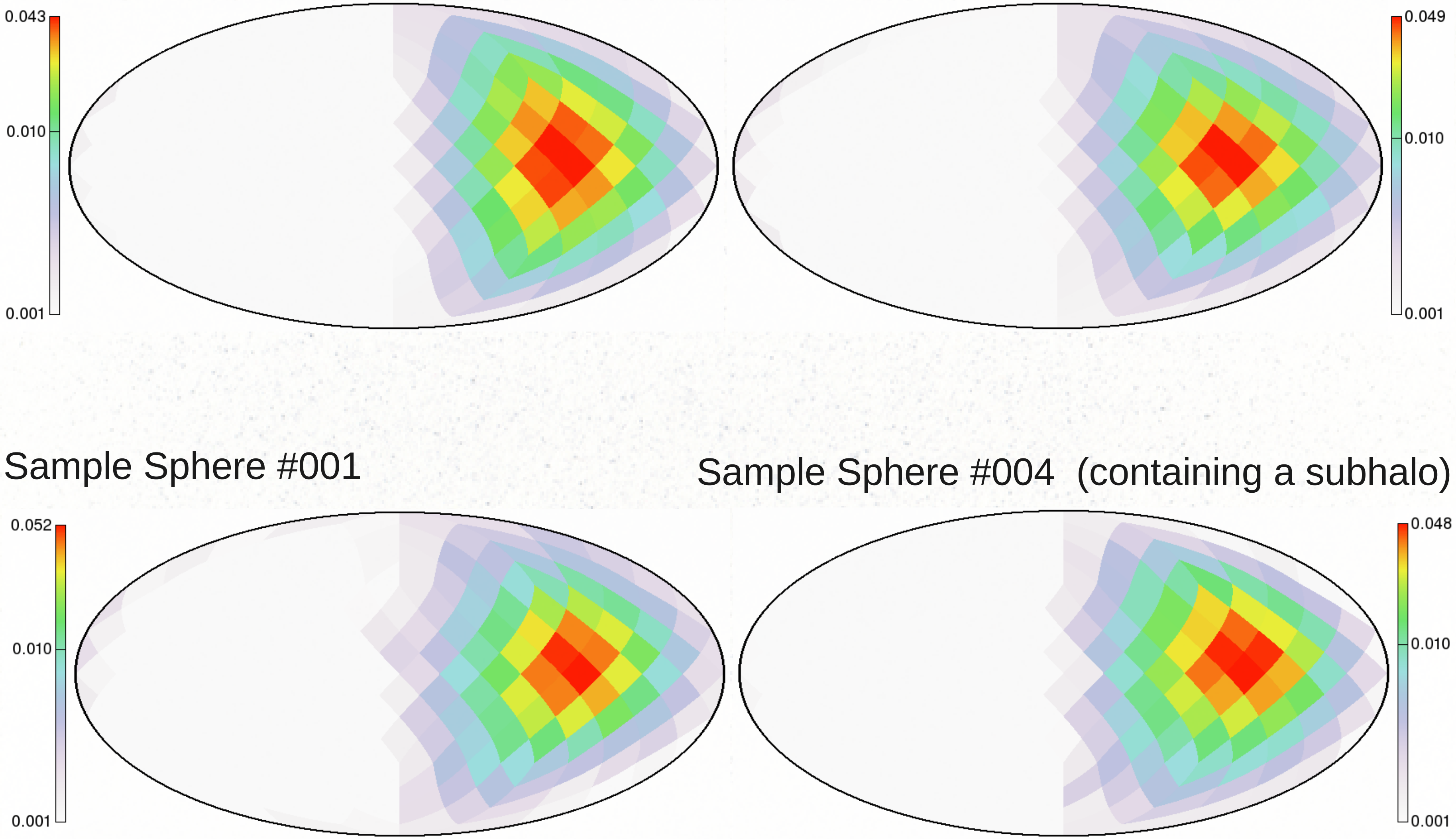
Sample Sphere #004 (containing a subhalo)



In Earth Restframe (v_{min} = 0 km/s)

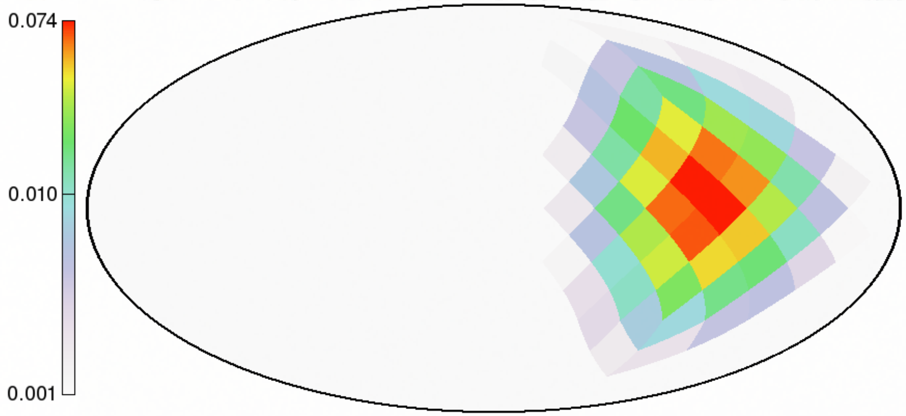
Maxwell-Boltzmann (isotropic) | Spherical Shell (8 kpc < R < 9 kpc)

Sample Sphere #001 | Sample Sphere #004 (containing a subhalo)

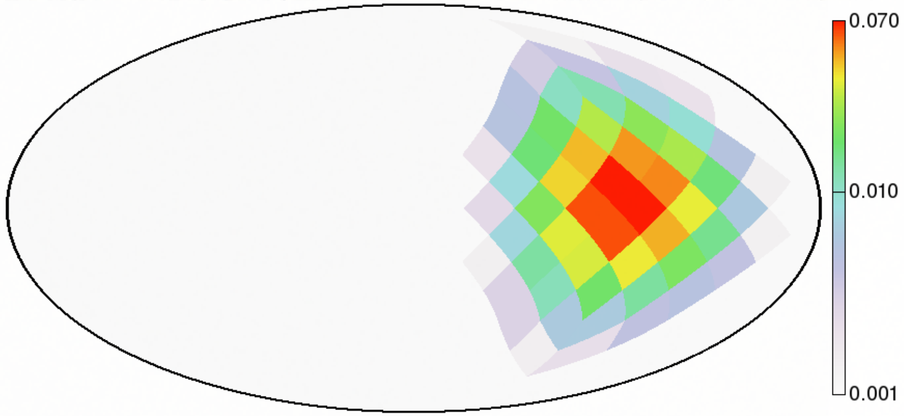


In Earth Restframe (v_{min} = 500 km/s)

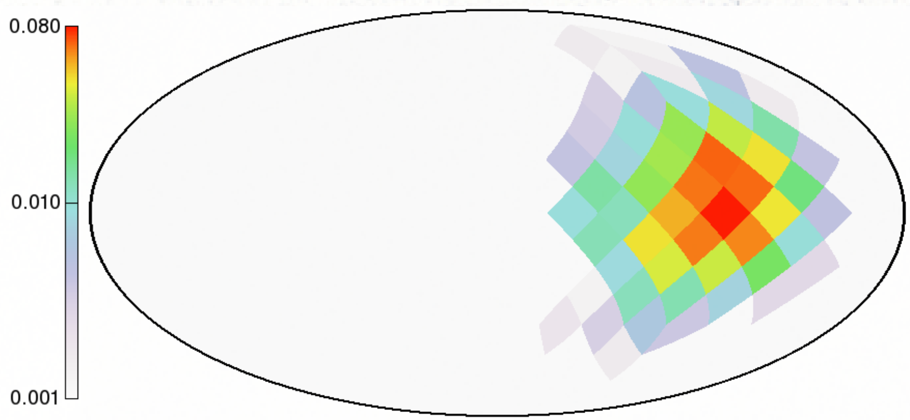
Maxwell-Boltzmann (isotropic)



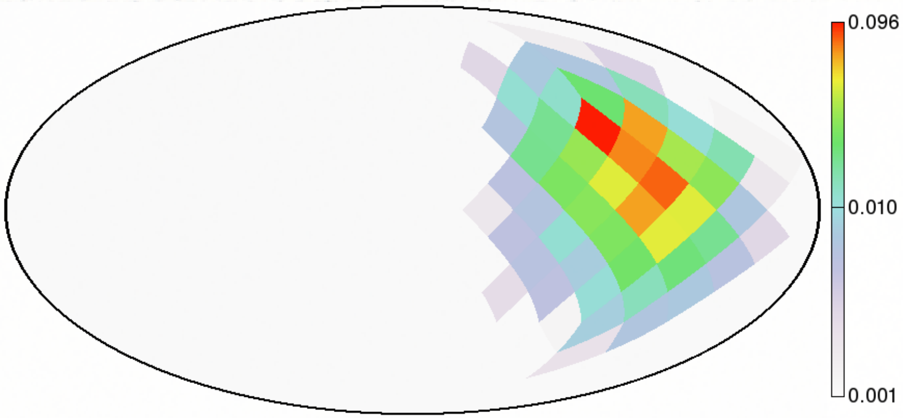
Spherical Shell (8 kpc < R < 9 kpc)



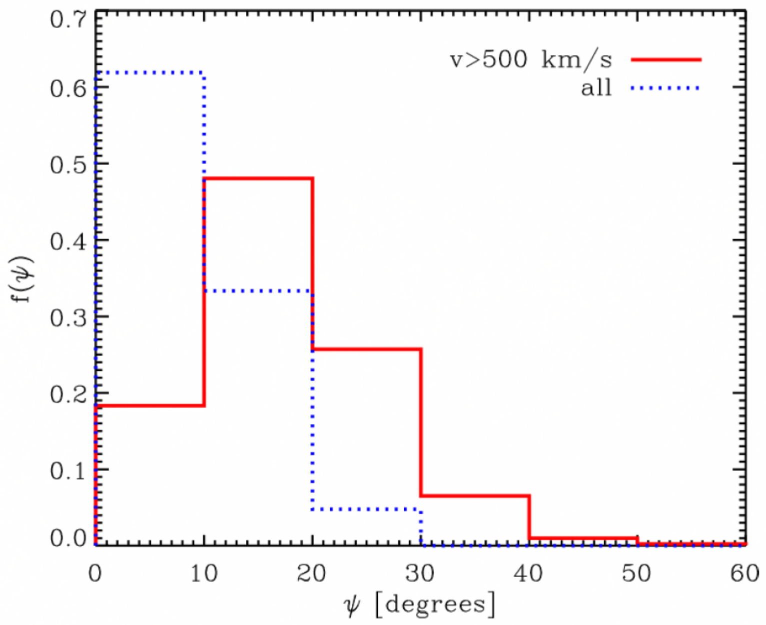
Sample Sphere #001



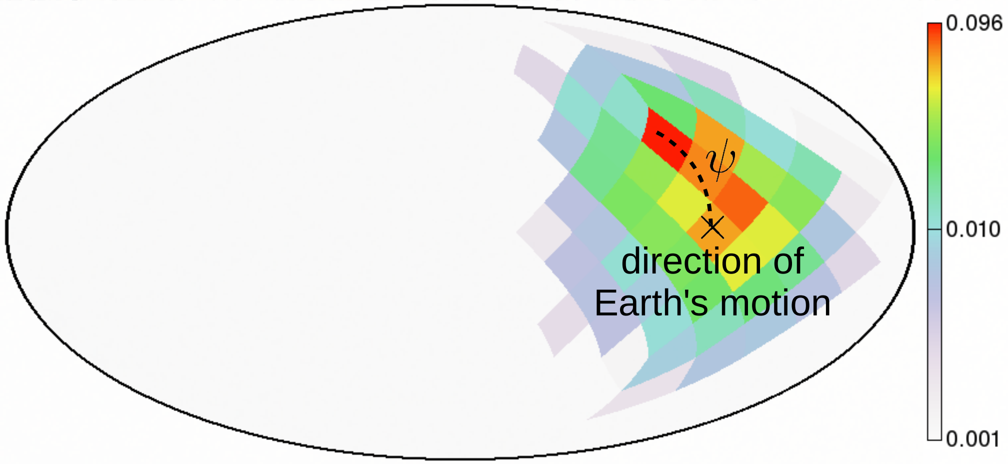
Sample Sphere #004 (containing a subhalo)



Hotspot Direction



Sample Sphere #004 (containing a subhalo)



At v_{min}=500 km/s the hotspot is more than 10° away from the direction of Earth's motion in ~80% of all cases!

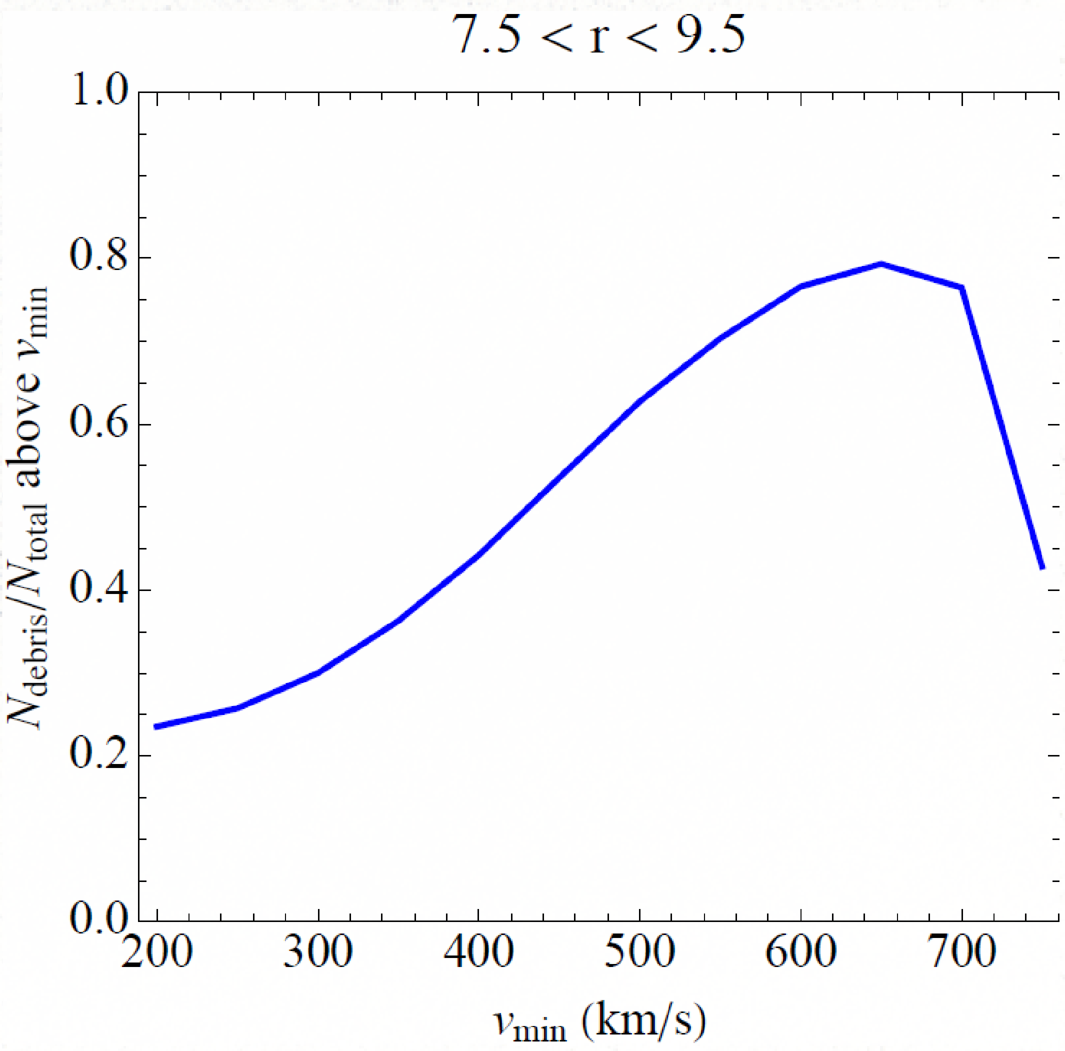
Velocity Space Substructure and Direct Detection

Recent work with M. Lisanti – **PRELIMINARY!!**

Study of the origin of the velocity space structure by tracking (sub)halo particles though time in the simulation.

Debris ≡ particles that were at some earlier time bound to a subhalo but are unbound at z=0.

1) The fraction of debris particles is quite large at high velocities!



Velocity Space Substructure and Direct Detection

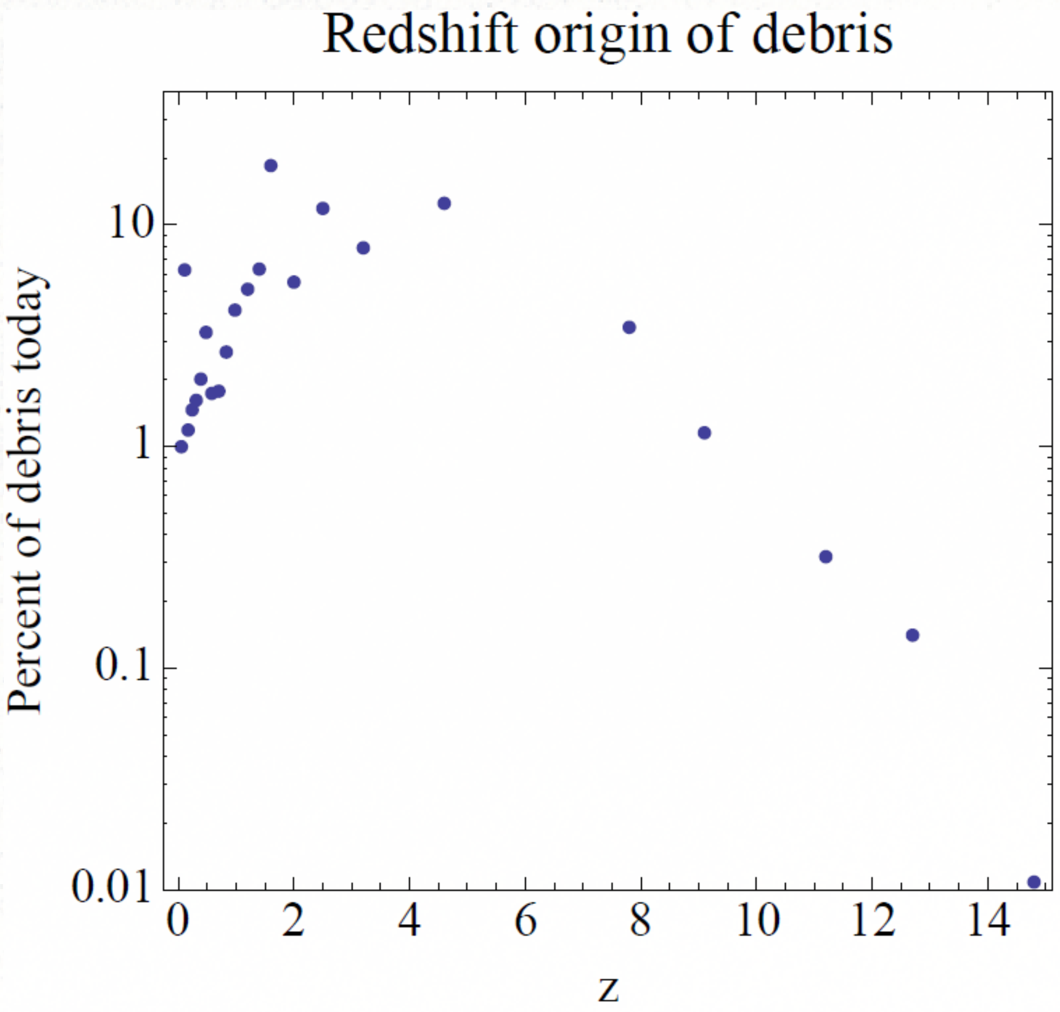
Recent work with M. Lisanti – **PRELIMINARY!!**

Study of the origin of the velocity space structure by tracking (sub)halo particles though time in the simulation.

Debris ≡ particles that were at some earlier time bound to a subhalo but are unbound at z=0.

1) The fraction of debris particles is quite large at high velocities!

2) Majority of debris is accreted after z=3 (in last 10 Gyr).



Velocity Space Substructure and Direct Detection

Recent work with M. Lisanti – **PRELIMINARY!!**

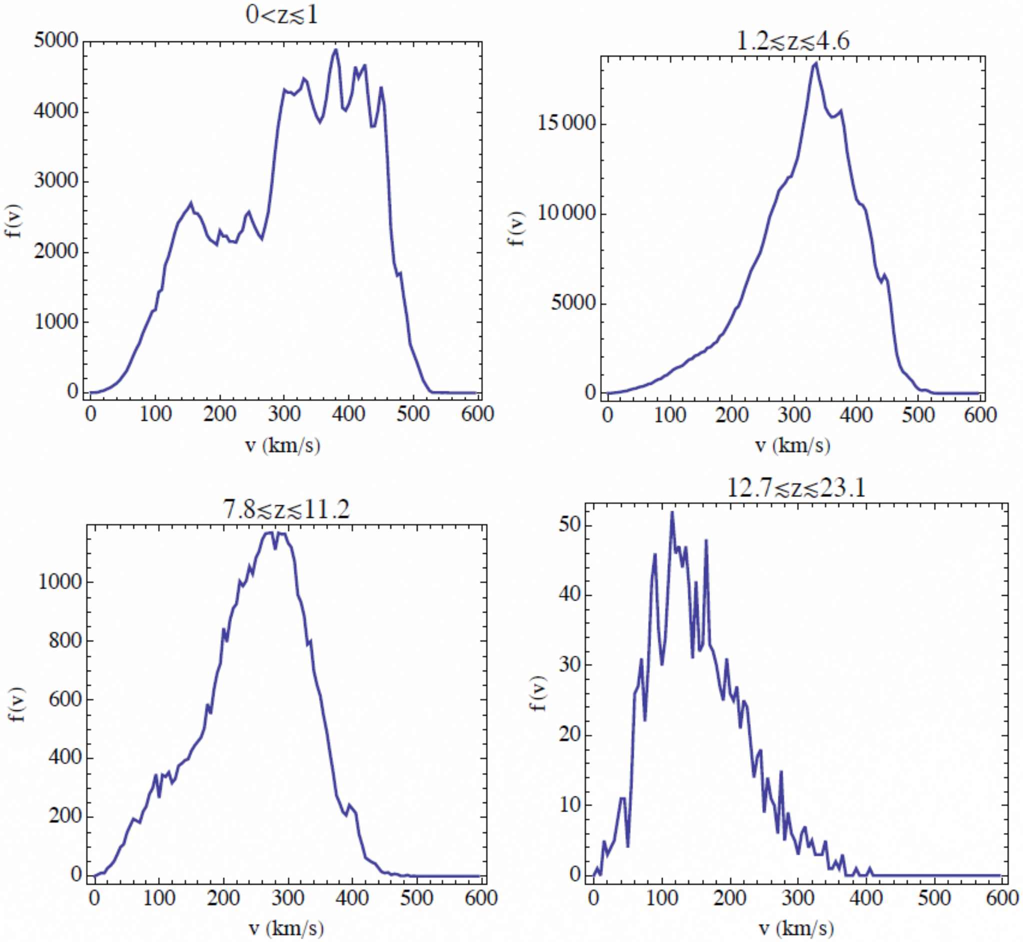
Study of the origin of the velocity space structure by tracking (sub)halo particles though time in the simulation.

Debris $\equiv$ particles that were at some earlier time bound to a subhalo but are unbound at z=0.

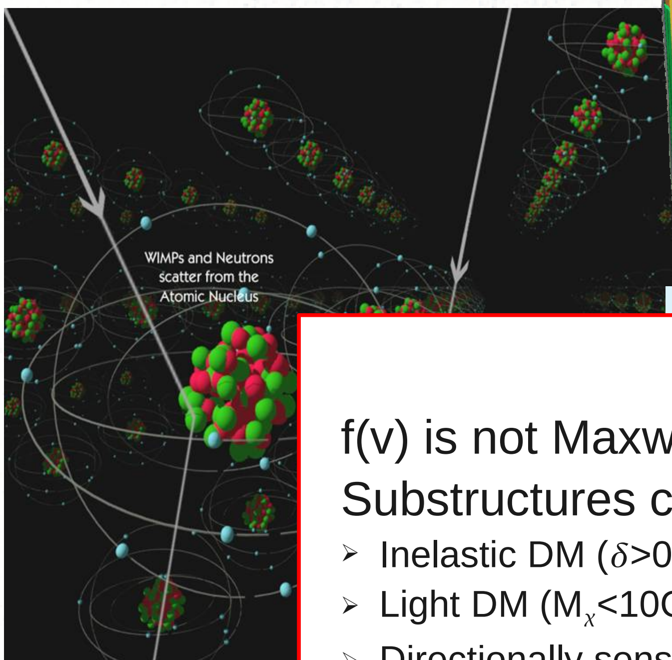
1) The fraction of debris particles is quite large at high velocities!

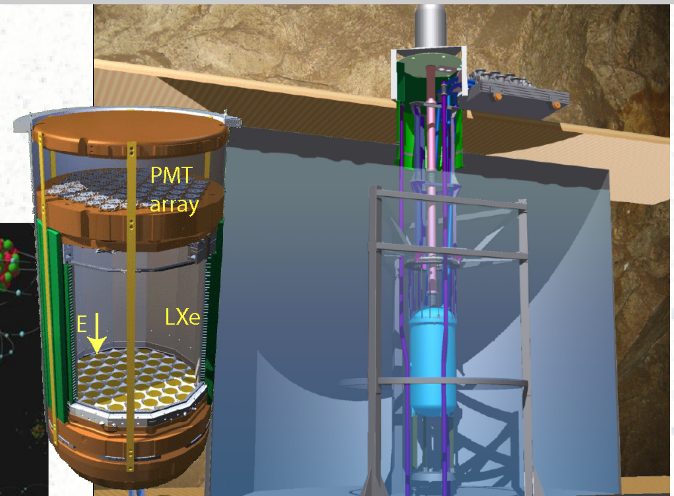
2) Majority of debris is accreted after z=3 (in last 10 Gyr).

3) Early accreted material is virialized. Later material shows large departures from Maxwellian.



Velocity Space Substructure and Direct Detection



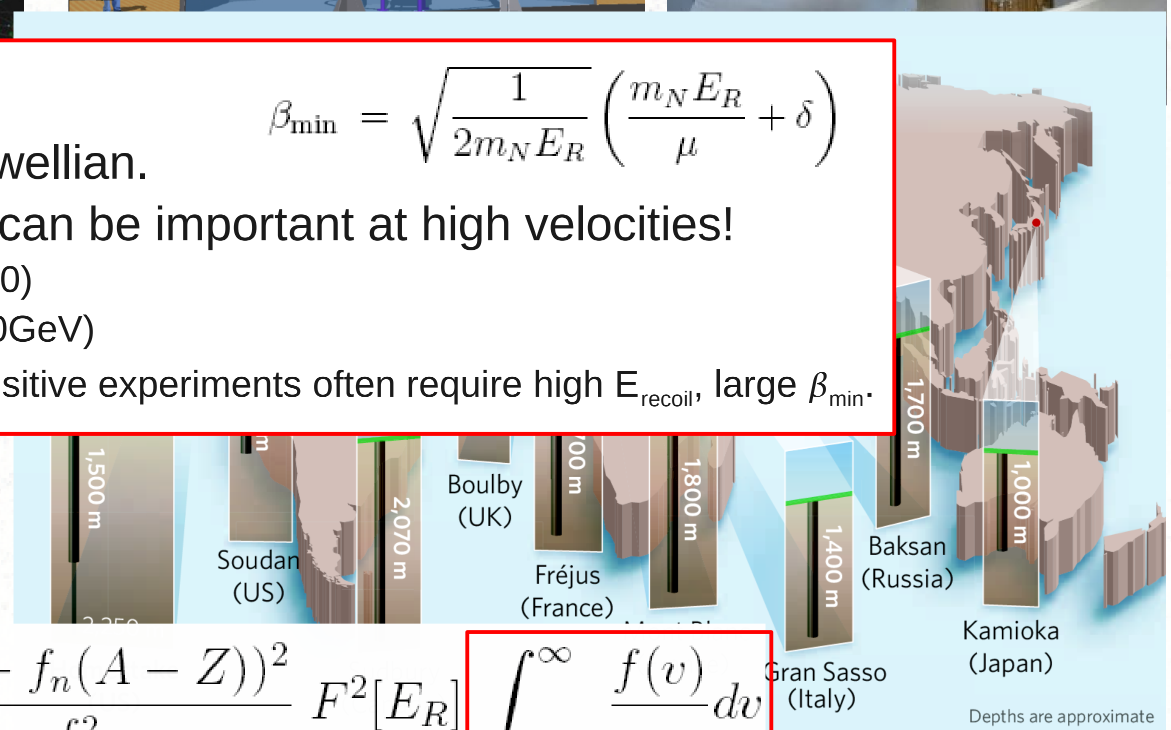


$$\beta_{\min} = \sqrt{\frac{1}{2m_N E_R}}\left(\frac{m_N E_R}{\mu} + \delta\right)$$

f(v) is not Maxwellian.

Substructures can be important at high velocities!

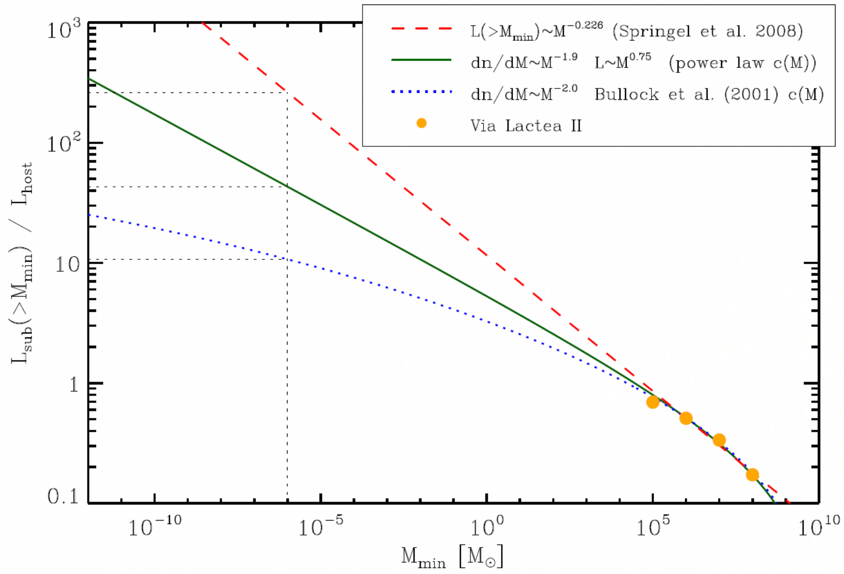
- Inelastic DM (δ>0)
- Light DM (M_χ<10GeV)
- Directionally sensitive experiments often require high E_{recoil}, large β_{min}.



$$\frac{dR}{dE_R} = N_T M_N \frac{\rho_\chi \sigma_n}{2m_\chi \mu_{ne}^2} \frac{(f_p Z + f_n(A-Z))^2}{f_n^2} F^2[E_R] \int_{\beta_{min}}^{\infty} \frac{f(v)}{v} dv$$

Uncertainties and Questions

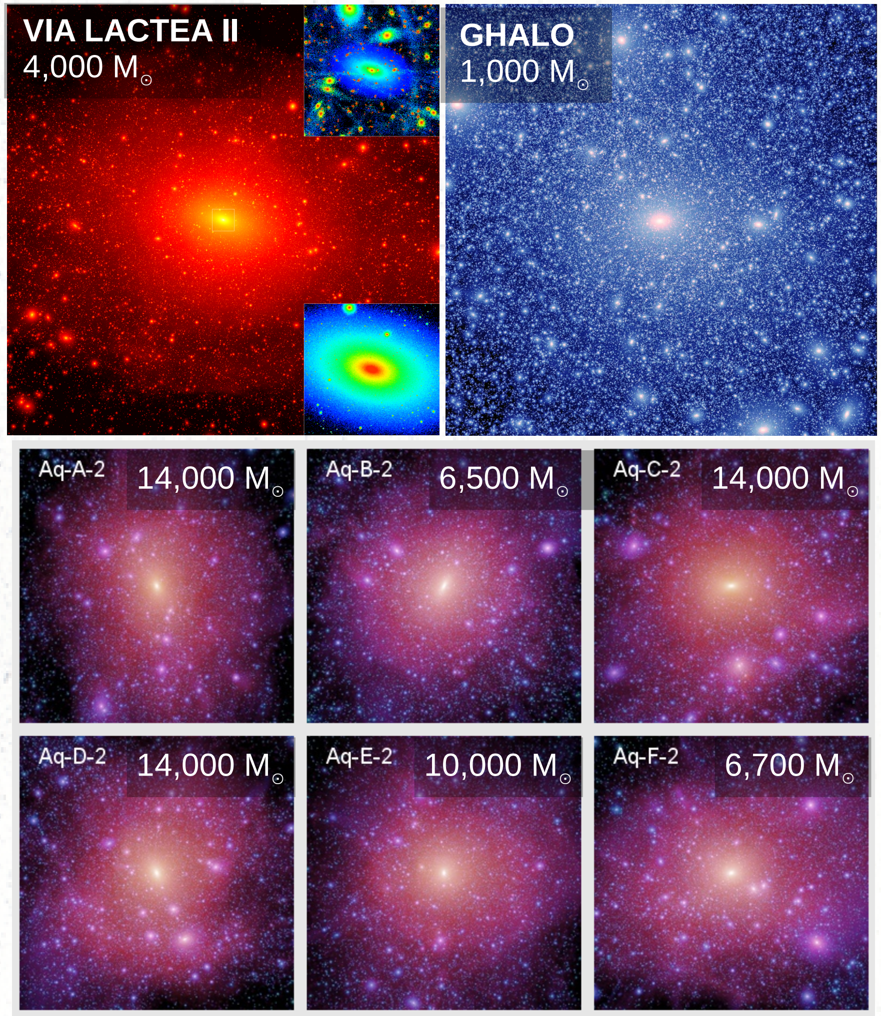
- **for CDM simulations**
  - extrapolation to lower masses
    - concentration-mass relation
    - tidal stripping & disruption
    - local phase-space structure



Uncertainties and Questions

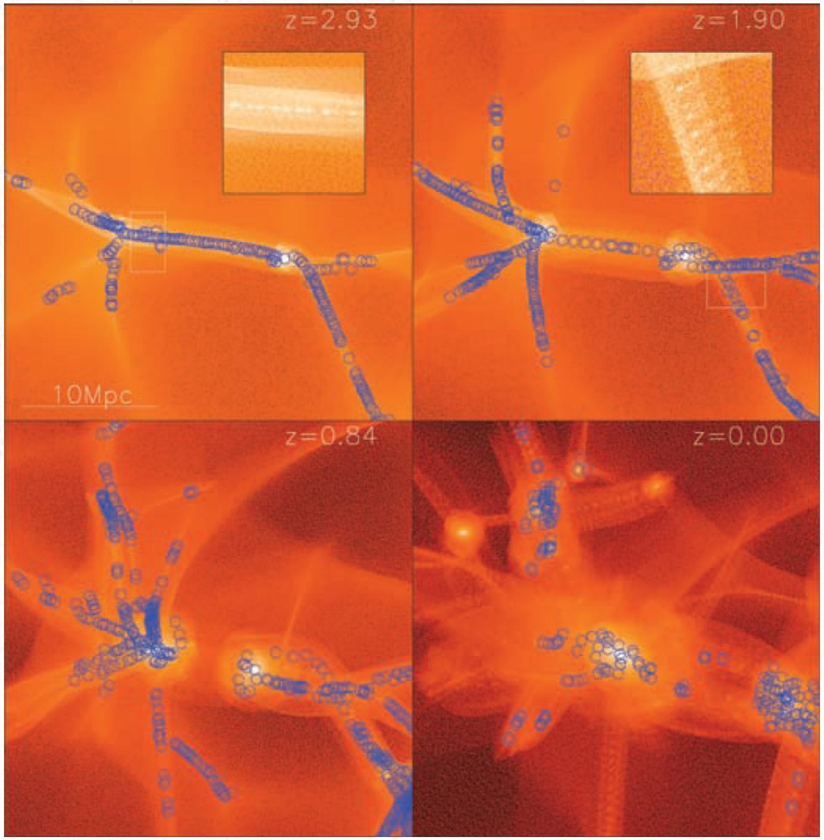
✯ for CDM simulations

- ➢ extrapolation to lower masses
  - concentration-mass relation
  - tidal stripping & disruption
  - local phase-space structure
- ➢ cosmic variance & cosmology
  - The 6 Aquarius host halos show considerable variation in merging history
  - σ_8, n_s affects the typical subhalo collapse time and hence properties



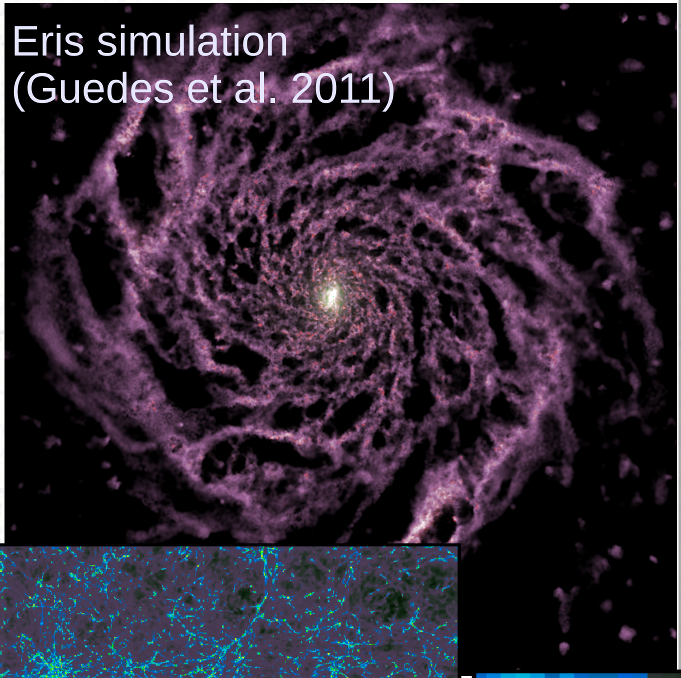
Uncertainties and Questions

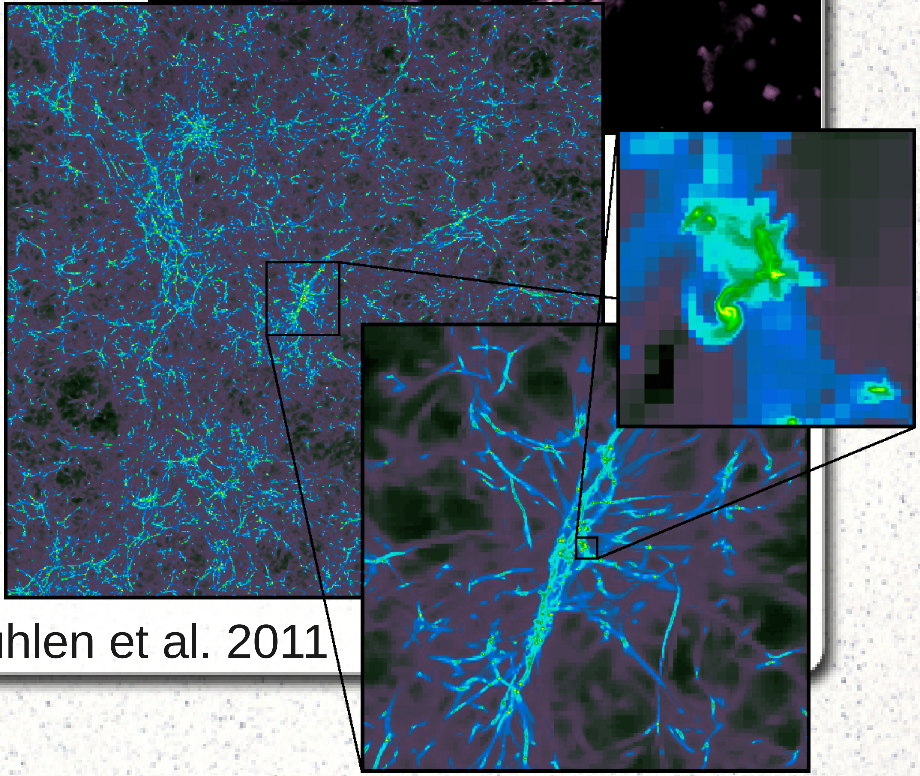
- **for CDM simulations**
  - extrapolation to lower masses
  - cosmic variance & cosmology
- **beyond "Cold Dark Matter"**
  - Warm (Tepid?), Self-interacting, ...
    - P(k) cutoff in the scales sampled by particles. How to avoid spurious fragmentation?
    - Non-negligible thermal velocities in the IC's.
    - No longer collisionless: Monte-Carlo method for δv (Davé et al. 2001)
  - Model dependent



Uncertainties and Questions

- **for CDM simulations**
  - extrapolation to lower masses
  - cosmic variance & cosmology
- **beyond "Cold Dark Matter"**
  - Warm (Tepid?), Self-interacting, ...
  - Model dependent
- **baryonic physics!**
  - "So, when are you going to include baryons in your simulations?"
  - Challenges:
    - expensive!
    - many ways to implement known important physics (star formation, supernova feedback, metal enrichment, interstellar chemistry, etc., etc.)
    - unknown important physics?





Kuhlen et al. 2011